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PHYSICAL VULNERABILITY DIVISION
DEPUTY DIRECTOR FOR TARGETS
TECHNICAL MEMORANDUM NO. 16

PVTM-16
30 SEPTEMBER 1955

FC

FIRE SPREAD IN URBAN AREAS

• WARNING •

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DIRECTORATE OF INTELLIGENCE
HEADQUARTERS UNITED STATES AIR FORCE
WASHINGTON, D. C.

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DIRECTORATE OF INTELLIGENCE
HEADQUARTERS UNITED STATES AIR FORCE
WASHINGTON, D. C.

CONFIDENTIAL

FOREWORD

This study was accomplished as a special project under the direction of Chief of Staff, U.S. Air Force, Directorate of Intelligence, Deputy Director for Targets, Physical Vulnerability Division. The special project group was headed by Mr. John M. Wolverton.

The Physical Vulnerability Division is examining the basic data collected in this study for the purpose of developing mathematical techniques for estimating the fire vulnerability of urban areas.

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PART I

INTRODUCTION

A. Historical Background

Fire has been used in warfare since ancient times. Relatively little scientific and engineering effort was directed toward solving the complex problems involved in the use of fire as a weapon, however, until the German Air Force attack on England early in World War II. Then the British attempted to apply to their own offensive air operations the knowledge gained in defense of their homeland against fire attack. Studies along similar lines were made by the United States, and apparently excellent coordination and exchange of information between these allied nations existed.

During the early phases of the war in Europe, the principal targets were industrial plants and other important installations. Therefore, the main objective was the direct ignition and destruction of the plants or buildings rather than the spread of fire from building to building. As the war progressed, large areas and even whole cities became targets for incendiary bombing, and more attention was given to the study of fire spread across open space. Even then, however, the immediate need for more effective incendiary bombs and ignition techniques tended to confine major fire research activities to the study of the starting and growth of fire within a structure. The exploding of atomic bombs over Hiroshima and Nagasaki in the final stages of World War II placed increased importance on the study of fire spread across open space. The Hiroshima and Nagasaki experience gave some indication of the large number of ignitions that could be expected from an atomic bomb explosion over an urban area and the size of the fire that might result. Some means for estimating the extent to which fires will spread from the area initially fired is of great importance for both offensive and defensive planning purposes in atomic or conventional incendiary attack. It was in recognition of the need for such means that the research project herein described was undertaken.

B. Research Objective

The specific objective of this project study is to evaluate the principal parameters affecting the spread of fire in urban areas so that the vulnerability of such areas to fires resulting from bombings can be estimated. No attempt is made to evaluate or analyze tactical factors or the effectiveness of different types of weapons in initiating fires.

C. Sources of Material

The sources of material were domestic and foreign books, research papers, and other documents, and pre- and post-strike aerial photography of certain European and Japanese cities which suffered incendiary or atomic bomb attacks during World War II.

The search for written material resulted in perusal of the collections of the Library of Congress, including the collections of the Office of Scientific Research and Development; the Captured German Documents Section, Adjutant General's Office, United States Army; the library of the Assistant for Operations Analysis, DCS/O, Headquarters USAF; and the library of the Physical Vulnerability Division, Deputy Director for Targets, Director of Intelligence, DCS/O, Headquarters USAF. Additional material or consultative assistance was obtained from the National Fire Protection Association; the National Board of Fire Underwriters; the Engineering Department of the Associated Factory Mutual Fire Insurance Companies; and the Division of Fire Research, Forest Service, United States Department of Agriculture.

D. General Considerations Governing the Progress and Spread of Fire in Urban Areas

Fire spread in urban areas, as considered herein, deals with the building to building spread of fire, resulting in what are called conflagrations or area fires. Webster defines a conflagration as "a raging destructive fire." Within fire protection circles a conflagration is usually defined as a fire which results in the destruction of a considerable number of buildings under a diversity of ownership, which spreads from building to building across streets or other open spaces from the area of origin, and which is of magnitude beyond the control of available fire-fighting facilities. Either of these definitions may be used to describe the wartime area fire. The principal and important difference between the peacetime conflagration and the area fire resulting from bombing attack is that the peacetime conflagration usually spreads from a single point of ignition, whereas the wartime area fire results from a large number of ignitions in a relatively short period of time. In either case the mechanics of fire spread from building to building are similar.

The term "fire storm" was coined in Germany in World War II to describe a conflagration characterized principally by a great inrush of air across the entire perimeter of the burning area.1/ This fire wind, which was caused by the great volume of hot gases rising from the mass fire area, tended to restrict outwardly spread of fire but made spread almost certain inside the burning area. The most famous fire storm is the great Hamburg fire, in which the fire-wind velocity possibly exceeded 100 miles per hour within and immediately adjacent to the burning area. Later on, a few of the conflagrations which occurred in Japanese cities also were called fire storms although induced wind velocities of less than 30 or 40 miles per hour were experienced. It is concluded that the severity of so-called fire storms may vary greatly, and that the severity is probably very closely related to the total fire or fuel load of the burning area. In the absence of a strong, natural ground wind, a fire storm is likely to develop in any large, combustible, densely built-up area in which hundreds or thousands of fires are initiated almost simultaneously. No attempt is made in this study to analyze separately the conflagrations in which fire storms were reported to have occurred.

1/ Physical Damage Division Report (ETO), U. S. Strategic Bombing Survey, Report No. 134b, April 1947, p. 47.

The spread of fire is due to heat which, transferred by one or more (usually a combination of three) agencies from a burning object to any combustible material, raises the temperature of the exposed material sufficiently to cause its ignition. Intensive heat falling on exposed combustible material, e.g., a wooden window frame on the facade of a building, may cause direct ignition of that material; but, if the heat falls on an incombustible substance, e.g., a wall of corrugated iron, it will be conducted through that substance and, if of sufficient intensity, will ignite combustible material in contact with the opposite face of the substance. The three methods by which heat is transferred across open space between buildings are:

(1) Radiation, in which heat is transferred without heating of the intervening medium. It is by this method that radiant energy reaches us from the sun.

(2) Convection, in which heat is transferred by the physical movement of heated matter, as by a current of hot air.

(3) Flying firebrands.

Wind, temperature, rain, humidity, terrain, building construction and contents loading, building heights, and a number of other variables affect the spread of fire across open space.1/ In order to understand the effect of these and other variables it is necessary to consider basic physical, chemical, and meteorological facts which govern the progress and spread of fire. These facts have been treated in detail by Clarence Goldsmith and the information in the remainder of this section is based upon his paper.2/

Flammable liquids never actually burn but are vaporized by heat, and the vapors mixing with air are ignited. The burning vapor-air mixture produces a flame, which is defined as a body of burning gas or vapor. In a second form of fire the material itself (charcoal, magnesium, etc.) oxidizes and produces heat with little or no flame. In general, fires in combustible material commonly used for or found within buildings, i.e., wood, paper, and textiles, pass through both stages. During the first stage of burning, the resins and other readily volatile substances in a solid combustible material are driven off by heat and burn, leaving almost pure carbon in the form of charcoal or coke. During the second stage, flame in contact with the charcoal results in further combustion with red or white hot embers, which heat other materials and spread the fire.

Frequently during the first stage of a fire, the heat is not sufficient to ignite the gases and vapors, so they rise in unburned jets.

1/ The Influence of Weather on the Extent of Damage Caused by Incendiary Bombs, Joint Target Group, Physical Vulnerability Section, March 1945.

2/ Clarence Goldsmith, Effects of Meteorological Conditions and Terrain Features on the Development and Spread of Fires, National Board of Fire Underwriters, 8 November 1944.

As the fire gains headway, these vapors ignite and burn, generally as long, colored flames with greatly heated products of combustion extending beyond. After a continuing fire is underway, flammable vapors are liberated from adjacent combustible material both by radiant heat and by the convection currents of heated air and the gases of combustion. These air and gas currents become so hot during a large fire that they ignite combustible materials considerable distances from the main body of fire. This type of ignition is entirely independent of sparks and flying firebrands and is termed "autoignition". Wood normally bursts into flame when subjected to a temperature of 750° F under conditions of rapid heating; and, if subjected to a temperature of 400° F for 20 to 30 minutes, wood will produce gases which can be readily ignited by a flame or spark. Other substances have autoignition temperatures varying over a wide range. This phenomenon is of prime importance in connection with the spread of peacetime conflagrations or wartime area fires. Its effect where wooden houses are concerned is obvious, and such structures are easy prey to radiant heat and hot convection currents. Where masonry structures predominate, it is likely that there will be overhangs of wood at the eaves and at window and door openings, which pocket heated air currents and materially speed up the spread of fire by radiation and convection currents.

Meteorological conditions such as wind, inversion, rain, humidity, and temperature influence the speed with which a fire will spread.

Oxygen is required to support combustion, and a draft is necessary to furnish a continuing supply of oxygen to the material undergoing combustion. A small draft or low wind velocity is conducive to slow fire spread, because the supply of oxygen is small. On the other hand, a strong draft or high wind velocity during the early stages of fire may also retard its spread, because the large volume of air pouring over the combustible material cools the material to such an extent that the generation of combustible gases is retarded. Experiments conducted by the National Board of Fire Underwriters indicate that the optimum draft or wind velocity during the early stages of a fire is approximately two miles per hour, or about three feet per second.

After a fire is well established, high wind velocities increase the draft, accelerate the burning rate, and increase the heat output. When a fire has gained conflagration proportions, the velocity of the wind on the lee of the fire is materially reduced and frequently reversed in direction by the pillaring of the heated air and products of combustion. Sparks and burning brands of considerable size are carried into the air by this pillar of hot air and, under certain wind conditions, travel extremely great distances. Although wind velocity on the lee of the fire is reduced as the cold front slides up the hot front of the pillar, the direction of progress of an ordinary conflagration is governed by the direction of the wind, which carries sparks and burning brands at the higher altitudes. The higher the wind velocity the more the pillar of heated air is pushed forward from the vertical. This holds heated air currents closer to the ground and increases the spread of fire by radiant heat by bringing the flame, which is a radiating body, closer to exposed buildings.

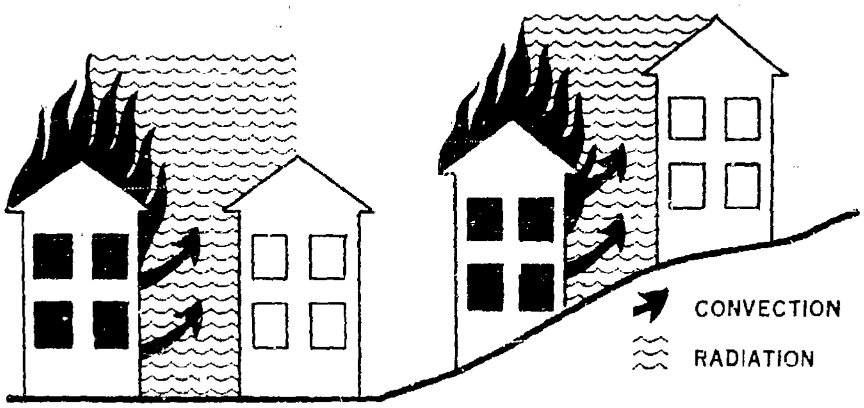
The prevailing temperature of the air influences the speed with which a fire spreads, because warm materials require less heat to bring

them to their ignition temperature than do cold materials of like nature.

Humidity has a twofold effect on the development of fire. First, high humidity in combination with inversion at the time of fire inception retards the formation of a pillar of heated air currents. The result is a smoky and relatively slow-burning fire due to lack of draft. Second, the average prevailing humidity in any section determines the moisture content of wood and other combustibles within roofed structures. When materials are moist, combustion is slow because part of the heat is expended in converting moisture to steam. In the initial stages of a fire, when heat output is relatively low, the moisture content of a material may well determine whether the fire continues to burn or not. After a fire has become well established, the effect of the moisture content of the materials becomes relatively unimportant because sufficient heat is available to dry them.

During rainy periods, the rain and the accompanying prevailing high humidity reduce the chances of building-to-building spread of fire, because, not only are the exteriors of exposed structures wetted down, but also convection currents of hot air are cooled and flying firebrands and embers are extinguished by the rain. Although the rays of radiant heat are not absorbed to any extent by the water droplets, the rain cools combustible materials which may be exposed to radiant heat. Rain, unless it continues over a considerable period, does not materially increase the humidity of combustible materials within roofed structures and, therefore, has essentially no effect on the initiation and growth of fire within such structures.

Terrain has an important influence on the spread of fire. The effect of wind in transmitting fire is accentuated when blowing uphill because the convection currents of air are more concentrated and, thus, hotter as they move up the hillside (see Illustration 1). When winds are low, the pillaring of hot gases is much more rapid and marked if a fire is progressing up a hillside than if progressing on level ground, and the rapid rise of hot gases increases the velocity of the draft supplying oxygen to the fire.



ILLUST. 1 TERRAIN EFFECT ON CONVECTION CURRENTS

Vegetation may influence the spread of fire during certain seasons of the year. Grass, weeds, and brush present little or no hazard during the growing season, but at other times they are highly flammable and subject to quick sweeping fires. Deciduous trees, when in leaf, retard the spread of fire because of their ability to absorb large quantities of radiant heat energy without bursting into flame.

It is evident from the preceding brief discussion of some of the factors which influence the spread of fire that, even if it could be developed, a mathematical formula containing all of the variables necessary to account for wind, moisture content, size and contents loading of buildings, terrain, etc., would be very complex. Also, there would be doubt as to the value of such a formula for use in predicting fire spread in a potential target city for which only limited information on physical characteristics was available. Therefore, it was decided early in this project study to evaluate only those factors which could be analyzed by means of photography, city maps, etc., and which could be used to estimate, with acceptable accuracy, the probability of fire spread in urban areas.

PART II

SEARCH AND SELECTION OF PHOTOGRAPHY

A thorough review of wartime and postwar research and of numerous publications pertinent to the subject pointed to the conclusion that building density, or the proportion of roofed area to ground area, has a definite bearing on the fire vulnerability of urban areas. However, nothing could be found indicating that an accurate appraisal of the effect of building density in urban area fires had ever been attempted.

Since it is possible to make accurate building density readings and damage assessments with the aerial photography used by target analysts, it was decided to attempt photographic evaluation of density as it affected damage attributable to fire in German, Italian, and Japanese cities which suffered large area fires during World War II. It was essential, therefore, to review all cities in this category and to select those (1) for which there was available both pre- and post-attack photography of good quality and of adequate scale (a contact scale of 1:10,000 was considered the minimum scale suitable for study) and (2) in which a fire line attributable to a single attack could be established. These requirements were established as a guide for selecting cities to be studied.

A complete catalogue of World War II Bomb Damage and Strike Reports is kept in the Military Intelligence Photo Interpretation (MIPI) files of the Deputy Director for Collection and Dissemination, Directorate of Intelligence, Headquarters USAF. A thorough search was made of these reports compiled on German, Italian, and Japanese cities. Initially, 22 German, 52 Japanese, and 2 Italian cities were indexed for photographic search. Most of these cities were later eliminated because more than one attack preceded the photographic reconnaissance and it was impossible to determine the fire area resulting from a single attack. MIPI bomb damage reports for the cities selected for study were copied in whole or in part and filed for use as references throughout the photographic analysis.

Selection of photography was limited initially to that available in the United States. It was found that available photography of German cities consisted of duplicates of negatives which had been selected from complete mission files in England. Much time was unavoidably expended viewing thousands of negatives of European and Japanese cities to obtain both pre- and post-attack photography, when photographic prints, photographic indices, or adequate plots would have made a quicker selection possible.

After initial review of the German cities, all except eight were eliminated because available information failed to meet the requirements mentioned previously. Even then it was necessary to request additional photography from the Air Ministry in England to obtain complete coverage for the cities selected (Hamburg, Essen, Darmstadt, Kassel, Cologne, Bremen, and Barmen and Elberfeld, the two townships of Wuppertal). Cologne and Bremen later proved to be unsuitable and were discarded.

At first the two Italian cities of Turin and Genoa were selected because the type of construction differed so greatly from that of either the German or the Japanese cities. Although they were subjected to heavy bombing attacks, large area fires did not result, so these two cities were discarded.

Suitable pre-strike photography was not available for most of the Japanese cities, but four were finally selected for study, including the two cities which had suffered atomic attacks (Hiroshima and Nagasaki) and two cities which had experienced conventional fire attacks (Kure and Sakai).

On receipt of all photography, photographic indices were prepared. These indices were of great value in the selection of the prints covering the cities. After satisfactory photography for a city had been collected, it was possible to study the effect of density on fire spread in that city.

PART III

PHOTOGRAPHIC ANALYSIS

A. TEST I - Density Evaluation

First, a city to be studied was divided into sections which appeared to be fairly homogeneous in building density and pattern of building layout. Wide rivers and large open areas were excluded, and the relative sizes of the individual homogeneous sections, although varying greatly, were not considered (see Illustration 2).

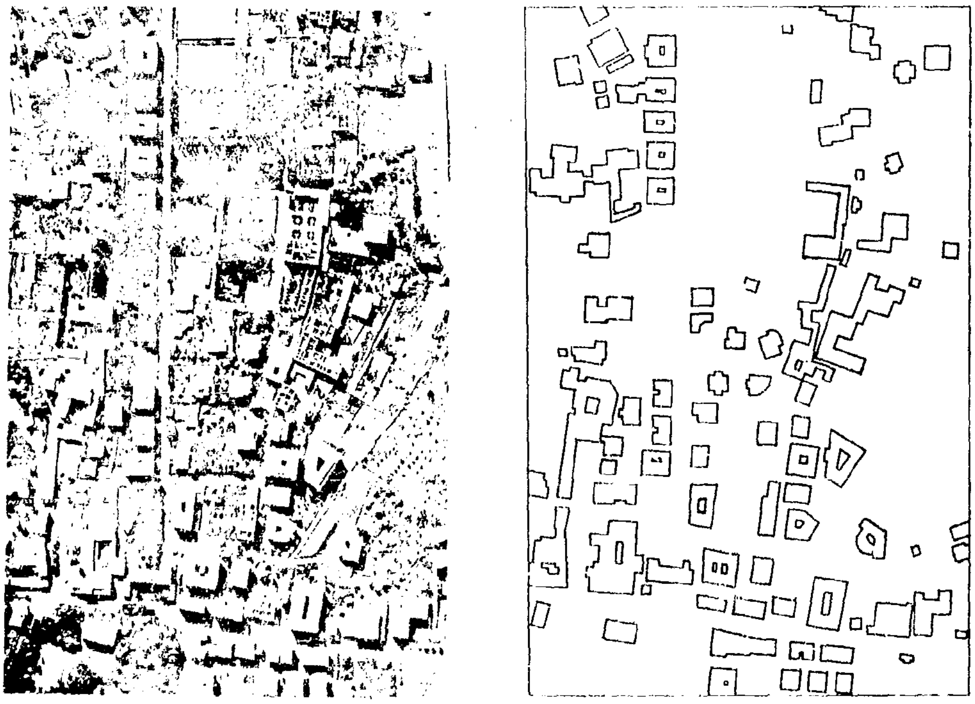
Next, a clear outline of all roof area had to be obtained. Several procedures were tried, and finally two methods, the stylus and the shading methods, were selected for use in all cities studied. If photography was of large scale and there was adequate separation between buildings, the stylus method was used. In this method, the building outlines were traced and transferred to sheet acetate by use of a stylus (see Illustration 3). In the other cases, the shading method was used. In this method, all areas not covered by buildings were shaded to display the building outlines (see Illustration 4). The shading method was considered the more satisfactory for outlining roof areas for Japanese cities where buildings were very congested.

Then building density was calculated by either of two methods, the square-counting or the area-measuring method. In the square-counting

ILLUST. 2 HOMOGENEOUS SECTIONING

method, a square grid was placed over the photograph, and the per cent of building density was computed by dividing the total number of building squares by the total number of area squares (see Illustration 5). This method was used where detail was poor or building separation was uniformly small throughout the area. In the area-measuring method, the ground area and the building area were actually measured with an areameter and building density was calculated by dividing building area by total ground area (see Illustration 6).

The township of Elberfeld (part of the city of Wuppertal, Germany) was selected as the first urban area to be studied for determining what relationship might exist between the degree of building density and the extent of fire damage. The southern part of the town from about the center to the outermost built-up areas was divided into homogeneous sections, and the percentage of damage in relation to building density in each section was calculated with the results shown in Table I. These results indicated no correlation between building density and damage.

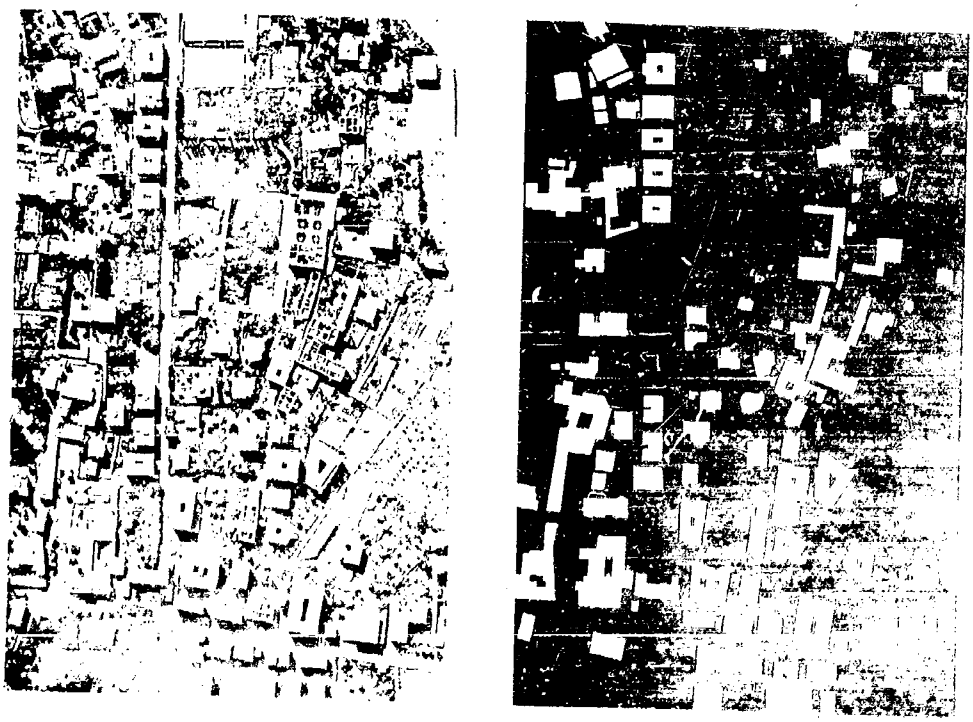


ILLUST. 3 STYLUS METHOD FOR OBTAINING ROOF OUTLINES

TABLE 1

DENSITY-DAMAGE IN HOMOGENEOUS S[illegible]

Building Density (%)	Damage (%)	Average Damage (%)
10-19	80	80
20-29	58	7[illegible]
	78	
	76	
	76	
	96	
30-39	79	64
	98	
	14	
40-49	100	88
	75	
50-59	94	94

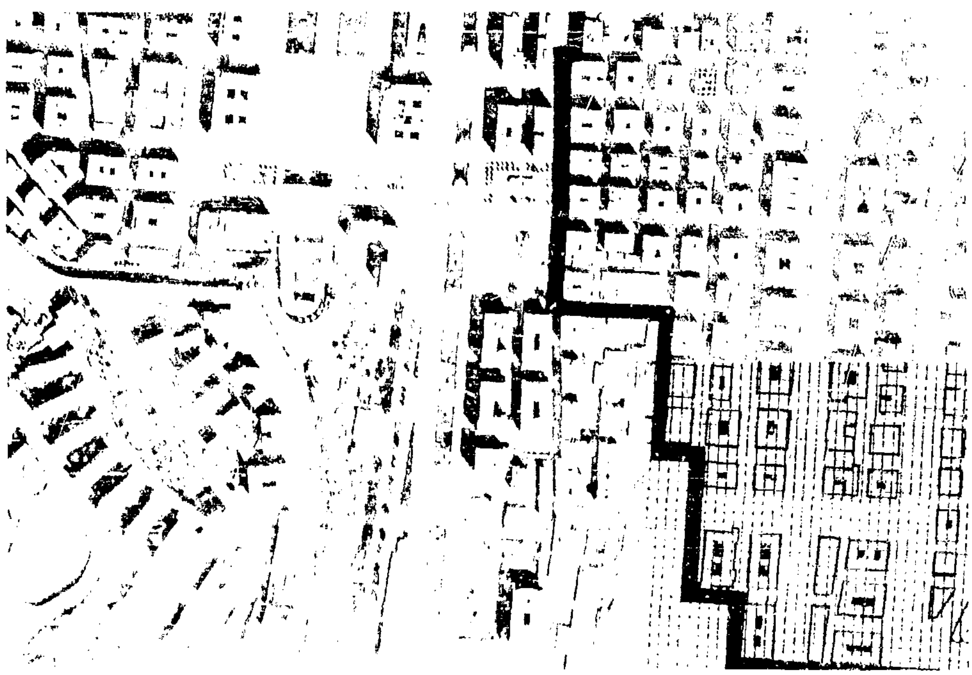


ILLUST 4 SHADING METHOD FOR OBTAINING [illegible]

The United States Strategic Bombing Survey (U.S.S.B.S.) report on atomic bomb effects in Hiroshima states that one of the most important factors contributing to fire spread is the compactness (built-upness or density) of combustible buildings, without which other conflagration factors, such as high wind, dry weather, and tall buildings, would have relatively little effect. This report also presents a graph (see Graph 1) showing the "Probability of Fire Spread in Various Amounts of Built-upness".1/ Although the fire perimeter of the burned area was established by ground survey, the data for the U.S.S.B.S. graph were obtained by photographic analysis in the following manner:

(1) Concentric circles of 5000-foot and 7000-foot radius were drawn with the ground zero (GZ), the point on the ground directly under the point at which the bomb detonated, as the center. In general, the perimeter of the burned area was inside the circular band of 2000-foot width; a negligible portion fell inside the 5000-foot circle and only a small portion fell outside the 7000-foot circle.

(2) Building densities of all built-up areas within the 2000-foot circular band were determined on pre-attack photographs.



ILLUST. 5 SQUARE-COUNTING METHOD FOR COMPUTING BUILDING DENSITY

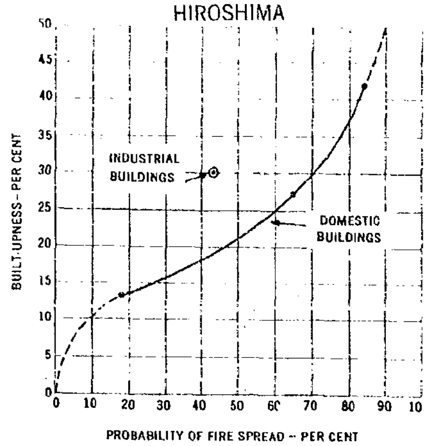
1/ The Effects of the Atomic Bomb on Hiroshima, Japan, Vol. II, Report No. 92, U. S. Strategic Bombing Survey, May 1947, pp. 16 and 40-42.

(3) The burned and unburned areas of each building density group within the 2000-foot circular band were measured on post-attack photographs.

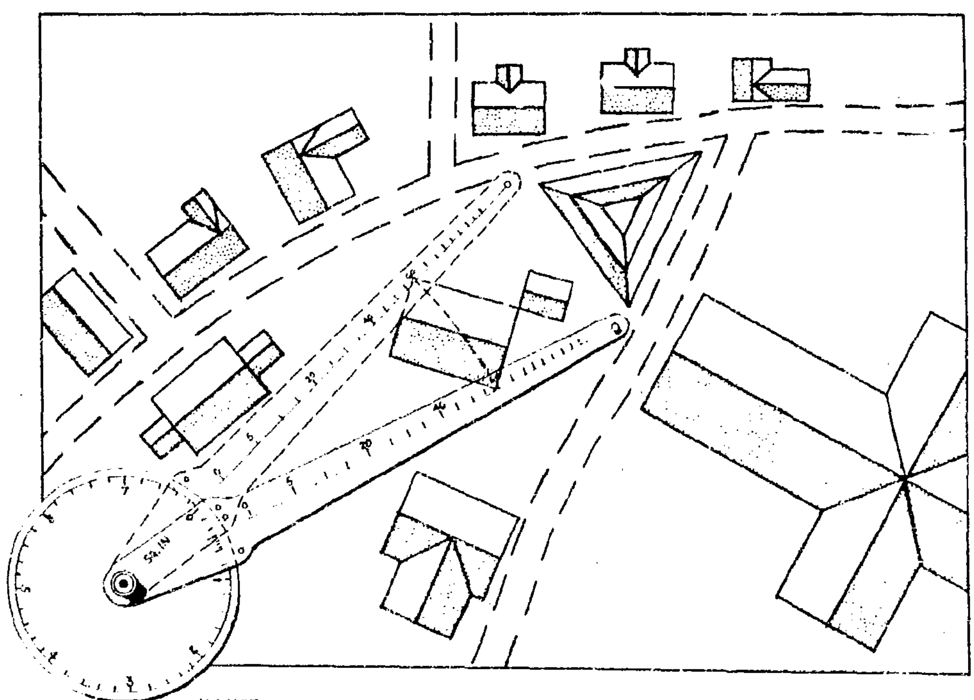
(4) Finally, the percentage of area burned in each building density group within the 2000-foot circular band was computed to obtain what was assumed to be the probability of fire spread in that building density, and these were plotted as shown in Graph 1.

Despite the negative results of the first building density-damage analysis in this study, it was deemed necessary, because of the conclusions drawn and presented by U.S.S.B.S., to try further analyses to determine whether a consistent relationship existed between building density and the amount of fire damage in German

PROBABILITY OF FIRE SPREAD IN VARIOUS AMOUNTS OF BUILT-UPNESS HIROSHIMA



GRAPH 1



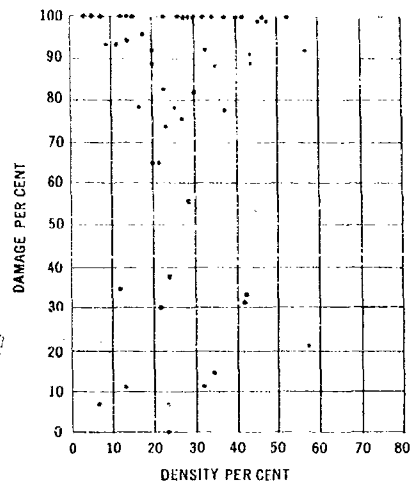
ILLUST 6 AREA-MEASURING METHOD FOR COMPUTING BUILDING DENSITY

cities. For this research, the southern part of Elberfeld was again used. Since the burn line was not symmetrical, as was the burn line in Hiroshima, it was decided to divide the town by a system of grids, arbitrarily set at 500 feet on a side, and to determine the building density and per cent of damage for each grid cut by the burn line (see Illustration 7). Again, no evidence was found of a consistent relationship between building density and fire damage. For example, some areas with 20 to 30 per cent building density suffered less than 10 per cent damage, while other areas in the same building density range suffered 75 to 100 per cent damage (see Graph 2).

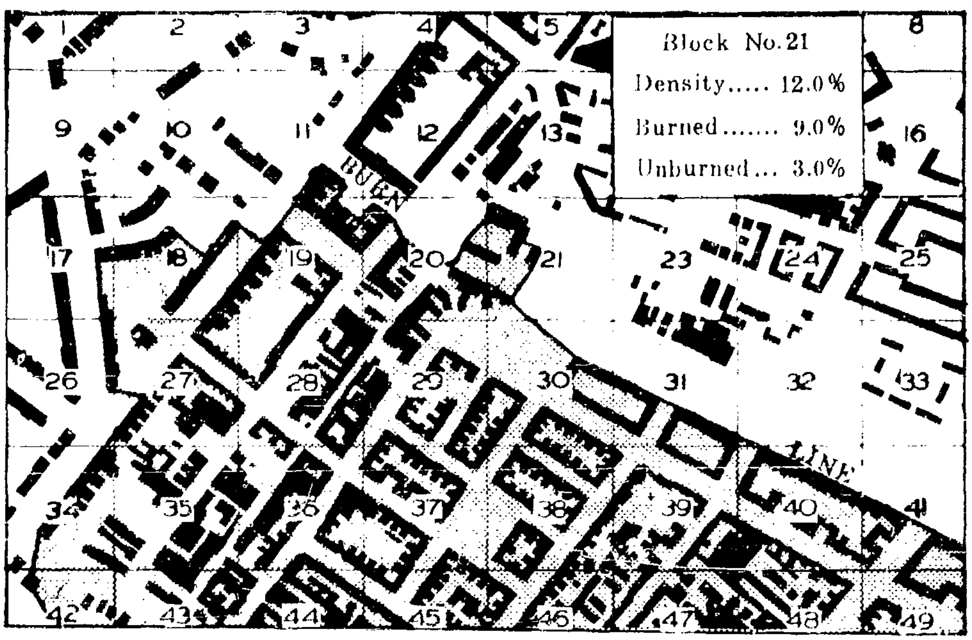
In another similar analysis of building density and its relationship to fire damage, Elberfeld was divided into city blocks and calculations were made on a block-by-block basis (see Illustration 8). However, there was still no indication of a consistent relationship between building density and fire damage.

DENSITY-DAMAGE

WUPPERTAL ELBERFELD



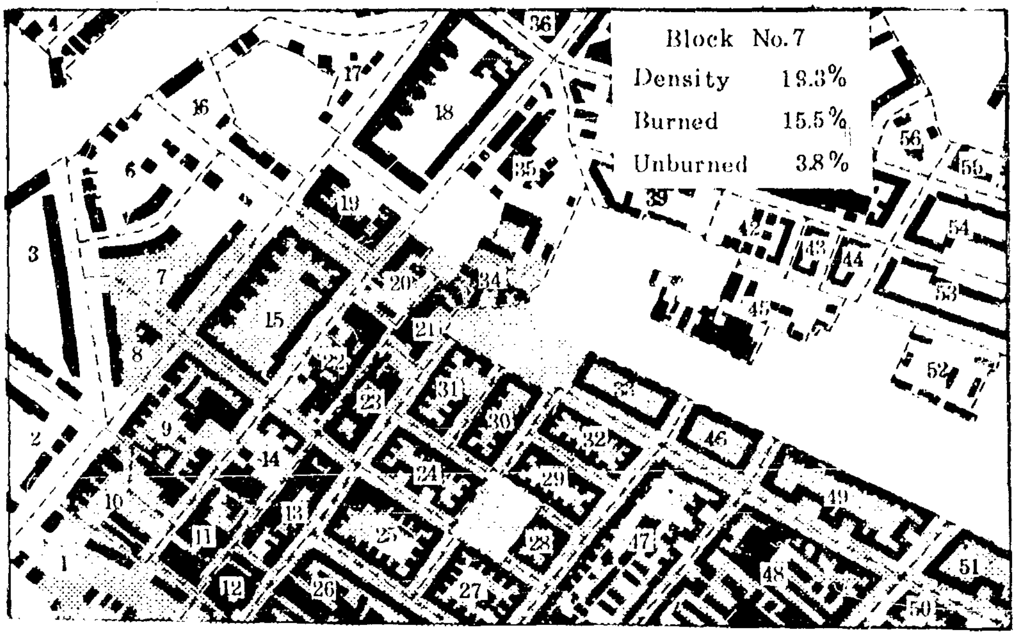
GRAPH 2



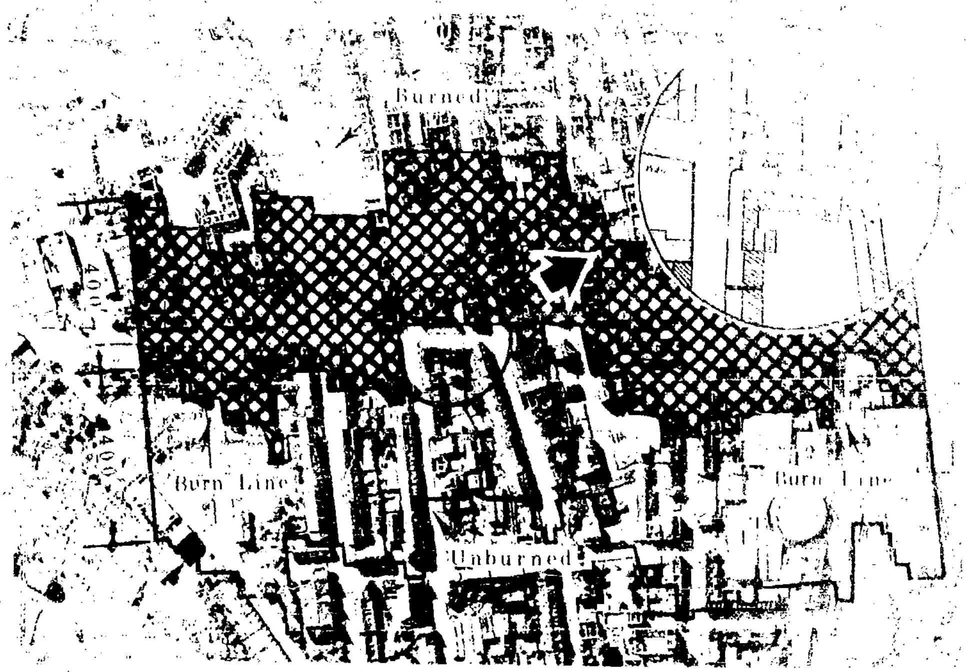
ILLUST. 7 THE 500-FOOT GRID METHOD FOR COMPUTING DENSITY-DAMAGE RELATIONSHIP

Since the burn line represented the perimeter of the burned area, it was thought improbable that the inconsistencies in the density-damage relationships were due to direct hits by incendiary bombs.

Continuing the search for a measure of the effect of building density on damage or fire spread, it was decided that the only additional analysis that could be made, using building density alone, would be to investigate the relationship between building density on the burned side and that on the unburned side of the burn line. It was necessary to establish a common basis for obtaining the building density on each side of the line. Examination of damage photography of several of the cities selected for study showed that fire spread across open spaces of 400 feet or more was the exception. In the few cases where it appeared that fire had possibly spread across distances in excess of 400 feet, there was reason to believe that direct incendiary hits had been recorded; if so, the damage observed was not the result of fire spread. Therefore, it was decided to use this measurement to establish a building density band, and a line was drawn 400 feet on each side of the line of burn (see Illustration 9). These 400-foot bands were divided into sections that were homogeneous with respect to layout of buildings. The relationship between building densities along each side of the burn line was then calculated for the cities of Elberfeld, Barmen, and Darmstadt and translated into graphs. It was found that, usually, the building density on the unburned side was lower than that on the burned side, partly because the burn line was drawn along the face of the burned buildings rather than along the face of the unburned buildings. There were numerous instances where the building density was zero on the unburned side. However, no consistent relationship was found between the building densities on the two sides of the burn line. Examination of the



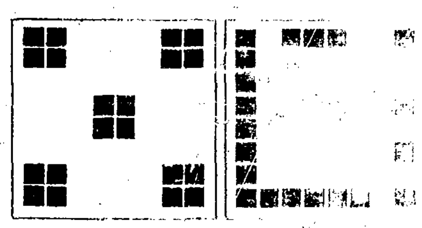
ILLUST 8 CITY BLOCK METHOD FOR COMPUTING DENSITY-DAMAGE RELATIONSHIP



ILLUST. 9 BURNED AND UNBURNED 400-FOOT BANDS

few cases where the density was greater on the unburned side than on the burned side provided no explanation; the distances between buildings opposite each other along the line of burn were average, and no features of construction which would normally be expected to arrest the spread of fire were evident. It was thought that in those few cases fire fighting might have been effective.

The foregoing attempts at developing a consistent relationship between building density and fire spread led to the conclusion that building density, by itself, is not a means by which a city's vulnerability to fire spread can be estimated. One explanation for this is that the arrangement of buildings in areas of the same building density may vary so widely as to have considerably different fire spread potentials (see Illustration 10). The proximity of buildings aligned along streets may allow fire to spread from building



ILLUST. 10 DENSITY PATTERNS

to building and 100 per cent damage may result even in areas of fairly low building density.

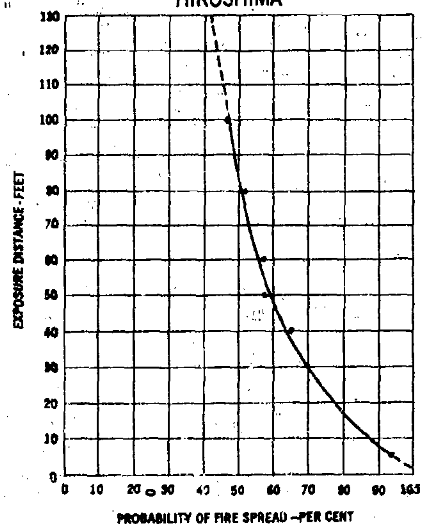
Once it had been established that building density alone can not be used for predicting fire spread, it was necessary to search for other factors which might have halted the spread of fire at the burn line in the cities being studied. It was possible that the wind conditions were unfavorable to fire spread, that fire fighting was effective, or that the distances between buildings were sufficient to render radiant and convected heat ineffectual.

Practically no information concerning wind conditions at the time of the attacks was found, and such information could hardly be developed through photo-analysis.

Although little specific information relative to the effectiveness of fire fighting was available for the cities selected for study, reports from other cities suffering incendiary attack indicated that fire departments were overwhelmed by the almost simultaneous ignition of buildings in many areas, making fire fighting efforts ineffectual. 1,2,3./

The U.S.S.B.S. report on Hiroshima includes a graph which shows a relationship between probability of fire spread at the fire perimeter and the exposure distance. 4/ For example, according to this graph, at a distance of 100 feet the probability of fire spread would be less than 50 per cent, but at a distance of 40 feet the probability would be 65 per cent (see Graph 3).

PROBABILITY OF FIRE SPREAD ACROSS VARIOUS EXPOSURE DISTANCES HIROSHIMA



GRAPH 3

1/ George J. B. Fisher, Incendiary Warfare, New York, 1946, p. 80.

2/ The Large Scale Raids on Hamburg in July and August 1943 (a report by the Police President and Local Air Protection Leader of Hamburg, secured in June 1945 by British and U. S. Intelligence Officers, Home Office, Civil Defense Department, Intelligence Branch), London, 1946 (available at the Library of Congress).

3/ Hans Rumpf, Der Hochrote Hahn (The Bright Red Rooster), Darmstadt, 1952, p. 98.

4/ The Effects of the Atomic Bomb on Hiroshima, Japan, Vol. II, Report No. 92, U.S.S.B.S., May 1947, pp. 41,43.

The data for the U.S.S.B.S. graph were developed by ground survey and by computation in the following manner:

(1) The entire perimeter of the burned area was surveyed and divided into segments within each of which the exposure distance from burned to unburned buildings varied within a narrow range.

(2) The average exposure distance for each segment was estimated.

(3) Segments having approximately the same average exposure distance were grouped and the total length of each group was computed.

(4) The percentage of the fire perimeter represented by each segment group was computed.

(5) Starting with the segment group having the shortest average exposure distance, the cumulative percentage of the fire perimeter represented by each segment group was computed.

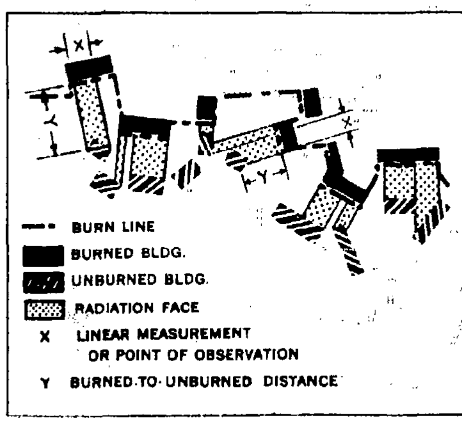
(6) Finally, each of these cumulative percentages was subtracted from 100 per cent to obtain what was assumed to be the probability of fire spread for the corresponding average exposure distance, and these were plotted as shown in Graph 3.

It was decided that a similar study could be made by photographic analysis of the German and Japanese cities selected.

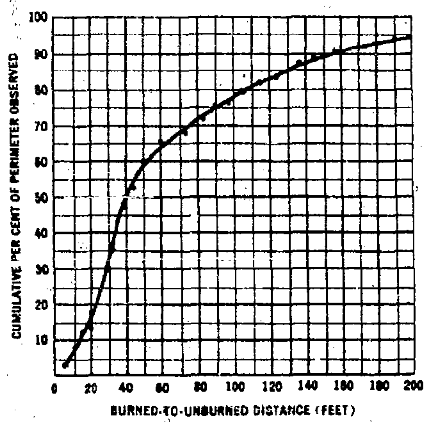
B. <u>TEST II - Distance Evaluation</u>

The township of Elberfeld (in Wuppertal) was selected for the first analysis. The burn line was drawn and the distance measured from burned buildings to unburned buildings. The linear measurement of the radiation face was taken as that part of each burned building directly facing an exposed unburned building. (See Illustration 9 Insert and Illustration 11)

Then the total of the linear measurements for each exposure distance was plotted as a cumulative percentage of the



ILLUST. 11 RADIATION FACES AND MEASUREMENTS



GRAPH 4

total fire perimeter (see Graph 4). Zero distances were observed where party walls, fire walls, etc., stopped fire spread. Although these zero distances were measured and recorded, they were not used in developing Graph 4 or any of the other graphs in this test or in subsequent tests because interest was focused primarily on spread of fire across open space.

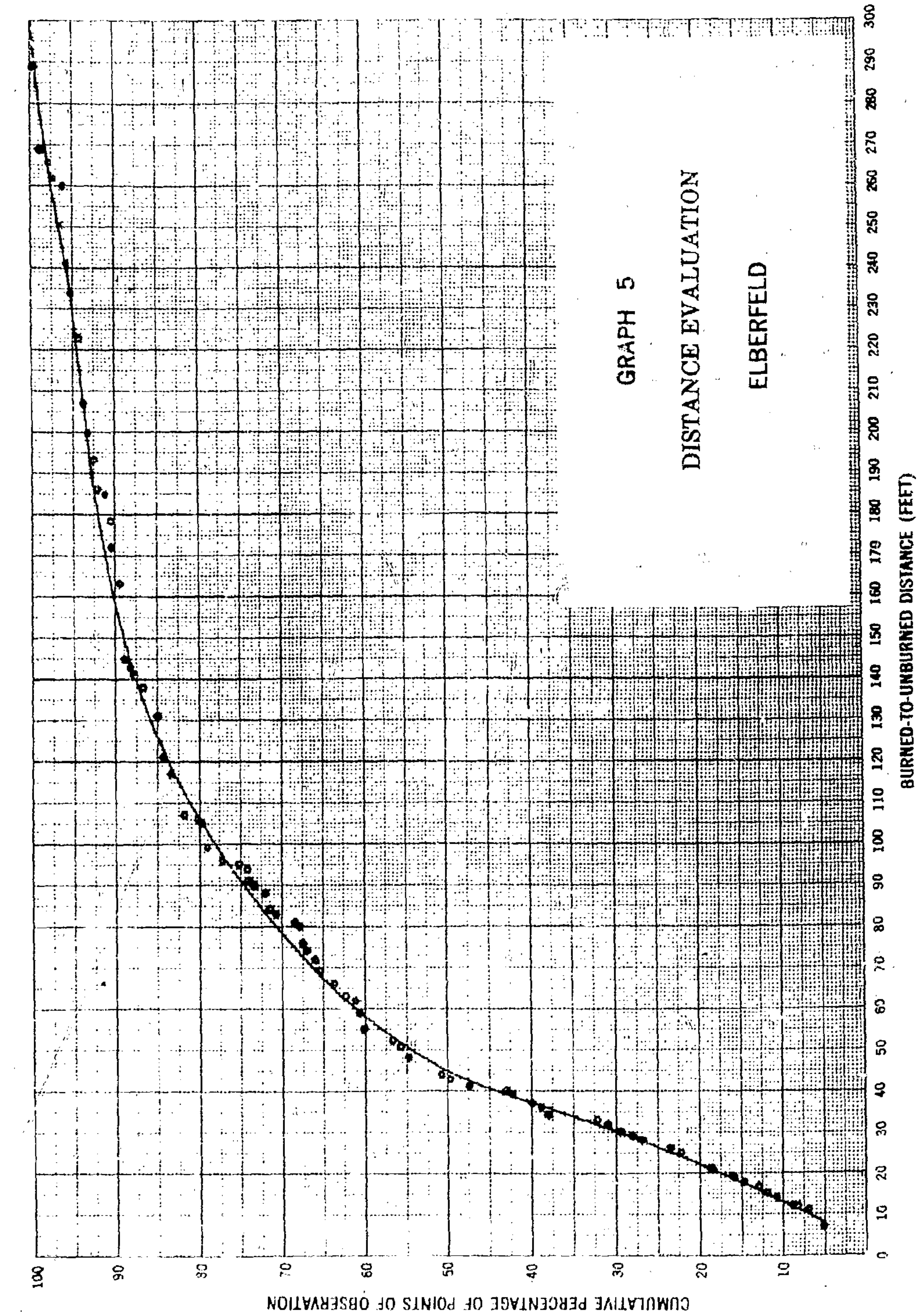
The U.S.S.B.S. curve for Hiroshima (Graph 3) and the cumulative curve for Elberfeld (Graph 4) showed comparable results for about 30 per cent of the fire perimeters. For example, 30 feet or less of open space stopped fire spread along 32.5 per cent of the fire perimeter in Elberfeld. This was in line with the probability curve prepared by U.S.S.B.S., which showed that the probability of fire spread across open space of 30 feet was 70 per cent, or the probability of a fire stopping at that distance was 30 per cent. However, 70 feet or less of open space stopped fire spread along 68 per cent of the fire perimeter in Elberfeld, whereas, according to the U.S.S.B.S. curve, the probability of fire spread across 70 feet was 53 per cent or the probability of a fire stopping was 47 per cent.

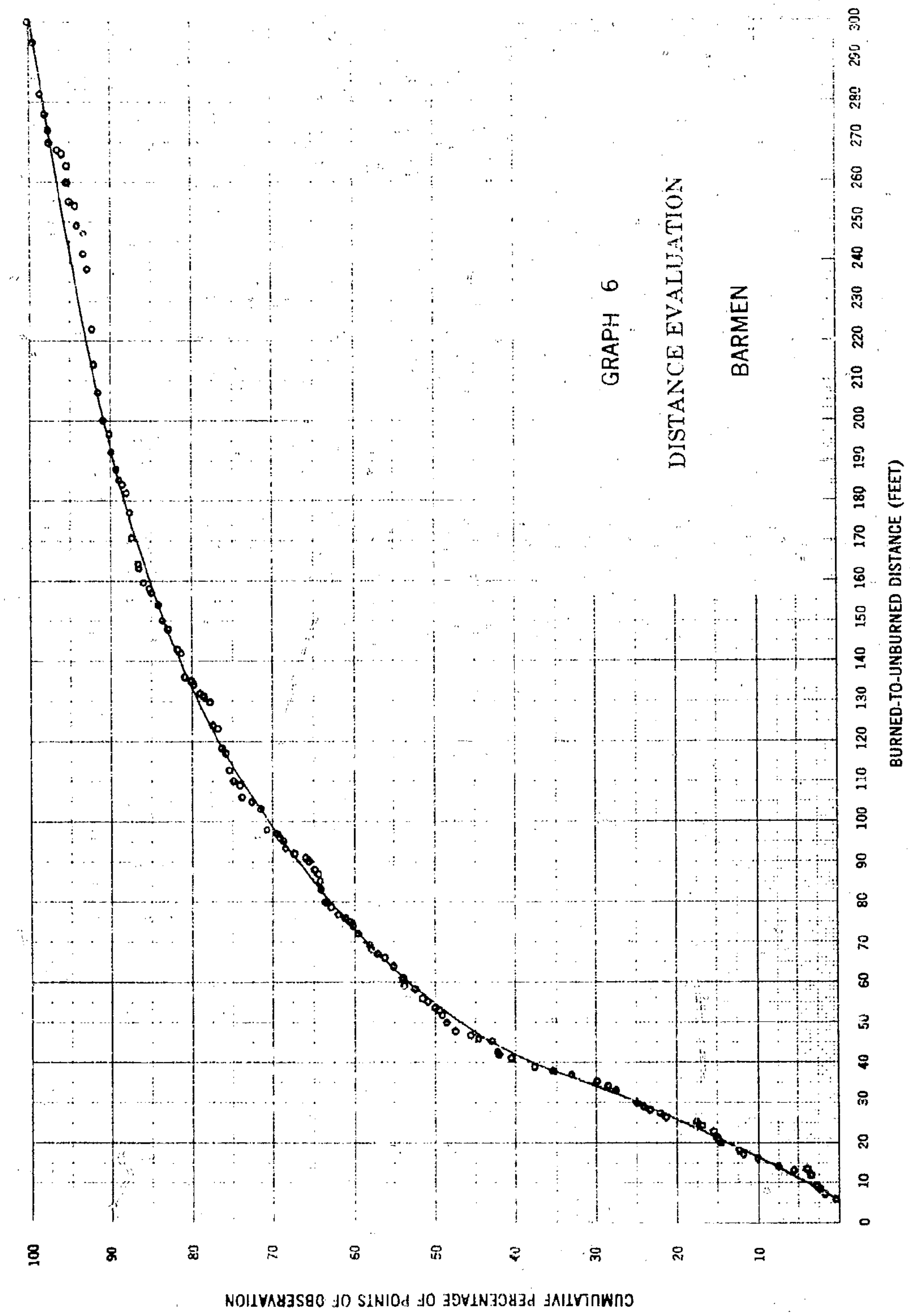
The close correlation in 30 per cent of the fire perimeter of these two cities seemed to warrant further research to determine if the wide variation in the remaining portion was due to differences in the characteristics of the two cities, or if there was some difference in the way the data for the curves had been accumulated.

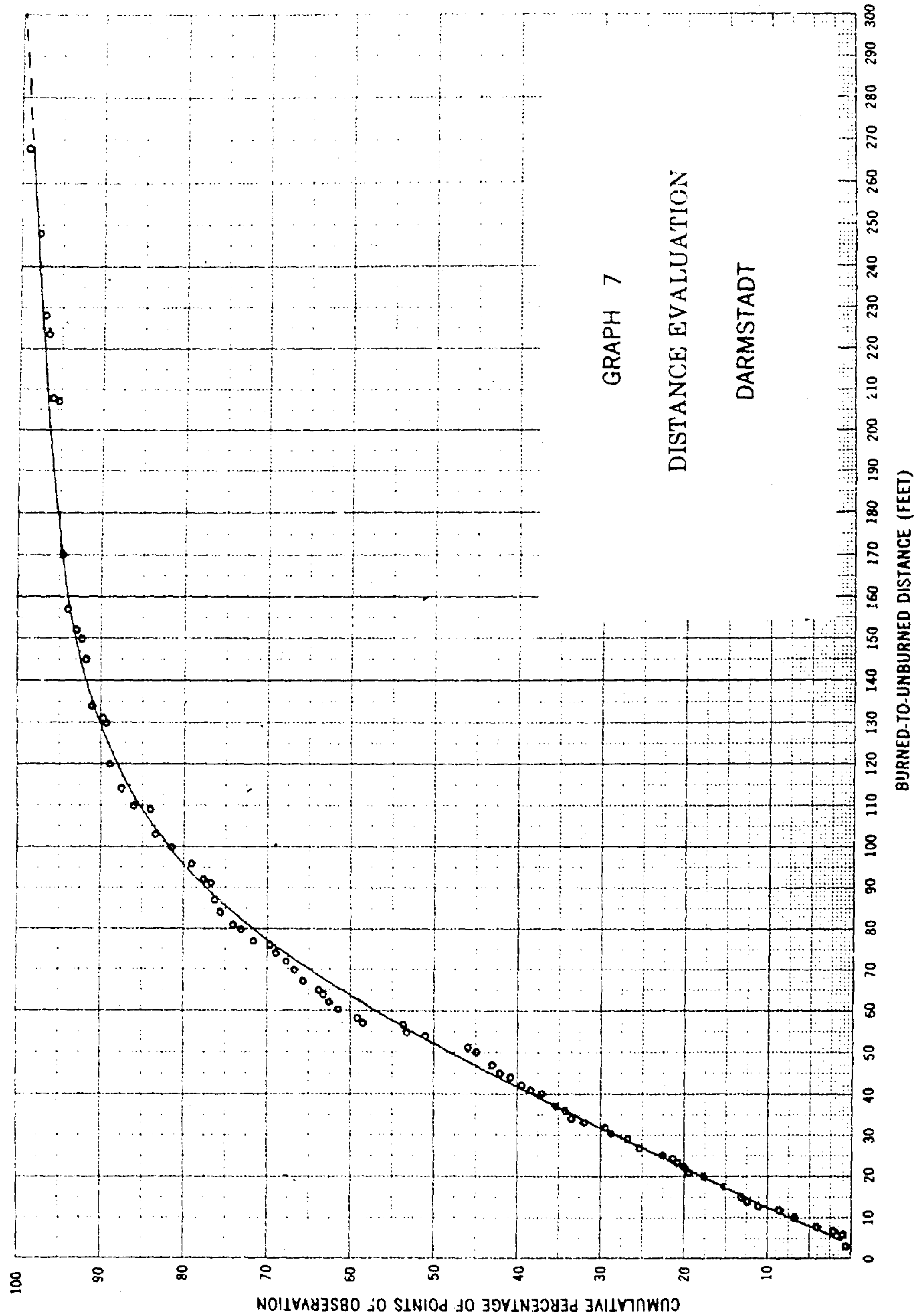
At this point, the reliability of results obtained by accumulating data as a percentage of the perimeter rather than by number of points of observation was questioned. A test was made in which data were accumulated by using both methods. The results were compared and found to be almost identical regardless of the method used. However, the points-of-observation method was adopted for all future analyses since it seemed to be a more reasonable basis.

Curves were then developed by the cumulative points-of-observation method for Elberfeld, the additional German cities of Barmen and Darmstadt, and the Japanese city of Kure (see Graphs 5, 6, 7, and 8). 1/

1/ In Part IV, Summary Discussion, similar curves are developed for Kassel, Essen, Hamburg, Hiroshima, Nagasaki, and Sakai (Graphs 22, 23, 24, 26, 27, and 29).


GRAPH 5
DISTANCE EVALUATION
ELBERFELD
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 6
DISTANCE EVALUATION
BARMEN
BURNED-TO-UNBURNED DISTANCE (FEET)
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION
100 90 80 70 60 50 40 30 20 10


GRAPH 7
DISTANCE EVALUATION
DARMSTADT
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
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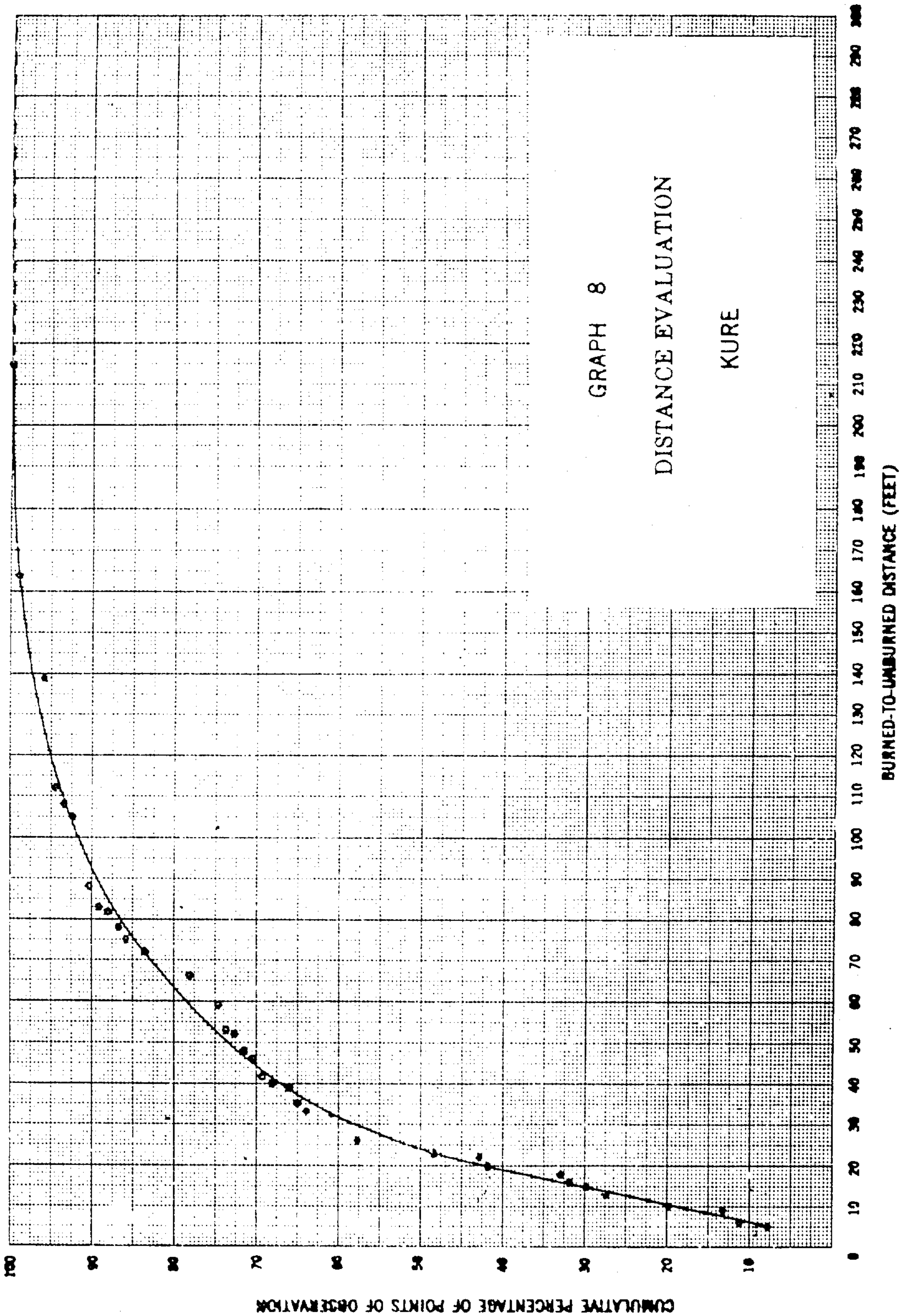
260
270
280
290
300


GRAPH 8
DISTANCE EVALUATION
KURE
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION

For purpose of comparison, these curves were then transferred to tabular form (see Table II), with a breakdown for each city, showing burned-to-unburned distances in 10-foot increments and the percentage of observations where the fire stopped at these distances (and all lesser distances) as related to the total number of observations.

TABLE II

DISTANCE EVALUATION

Burned-to-Unburned Distance (in Feet)	Cumulative Percentage of Points of Observation at which Fire Stopped			
	ELBERFELD	BARMEN	DARMSTADT	KURE
10	7.0%	4.0%	7.5%	19.0%
20	17.5	14.0	17.5	41.5
30	30.0	25.0	28.0	58.0
40	44.5	38.0	38.0	67.0
50	54.5	47.0	48.0	73.5
60	61.0	53.0	57.0	78.5
70	66.5	58.5	65.0	83.0
80	71.0	63.0	71.5	86.5
90	74.5	67.0	77.5	89.5
100	78.0	70.5	82.0	91.5
110	81.0	74.0	85.5	93.5
120	83.5	76.5	88.0	95.0
130	86.0	79.0	90.0	96.5
140	87.5	81.5	92.0	97.5
150	89.0	83.5	93.0	98.0
300	100.0	100.0	100.0	100.0
Number of Points of Observation:	162	238	170	293
Graph Number:	5	6	7	8

The data for Elberfeld, Barmen, and Darmstadt showed fairly good correlation. However, the data for Kure suggested that fire spread was halted by much shorter distances between buildings in Japanese cities than in German cities. For example, fire was stopped by open spaces of 20 feet or less at 41.5 per cent of the observations in Kure, as compared with 17.5 per cent of the observations in Elberfeld, 14 per cent in Barmen, and 17.5 per cent in Darmstadt. Although the results of this test were surprising, there was a plausible explanation.

Burning time, or the time during which radiant heat is transmitted, is governed by building density, construction, height, and contents loading. It was thought that the difference in the pattern of fire spread in the German cities as compared with the Japanese city was largely due to differences in their burning time. Reference to research conducted by the Japanese confirmed this explanation. Japanese houses, being small in volume and of rather light, wood construction, were consumed rapidly by fire. 1/ The Japanese research indicated that the time required for one of these structures to burn with high radiant heat emission was as little as 12 to 15 minutes. If true, fire fighting in the nature of a few buckets of water on exposed surfaces could have prevented ignition of many buildings separated by short distances along the fire perimeter. The effects from radiation were reduced to a minimum, not only because the burning time was so short, but also because nothing was left to act as radiating surfaces after the flames had subsided. On the other hand, the German cities contained mainly multistory masonry buildings with combustible roofs and interiors, including heavy woodwork and furnishings. When the combustible portions of these buildings were consumed by fire, the outside walls became heated and were generally left standing to act as radiating surfaces for considerable periods of time. Study of pre-attack photography showed that construction was relatively uniform in all the German cities selected, and any differences that might exist would undoubtedly average out when reviewed as a whole. Though of a different type, construction in the Japanese cities was even more nearly uniform.

It was apparent that construction and contents loading had the greatest effect on burning time and, hence, was probably the factor which caused the variation in the distance required to halt fire spread in the German cities as compared with the Japanese city. While it was possible to obtain workable data on construction from aerial photography, no information was available on contents loading of buildings at the time of attacks. Nevertheless, it was evident that curves developed for German cities would not be consistent with those prepared for the Japanese cities, and that these two types of cities would have to be treated separately.

Although the cumulative curves developed for the German cities in this test were similar, there was sufficient variation between the individual cities to warrant investigation of the effects of other factors, such as building density and building volume, on distances required to stop spread of fire. Either building density or volume would constitute a rough measure of the fire or fuel load in a built-up area. The next test was designed, therefore, to see if building density represents a usable measure of fire load as it effects the distance required to stop spread of fire. It was expected that as building density increased the distance between burned and unburned buildings would also increase.

1/ Kim'ichiro Fujita, <u>Fire Spread Caused by Radiant Heat and Methods of Prevention</u> (available in microfilm copy at the Library of Congress).

C. TEST III - Density-Distance Evaluation

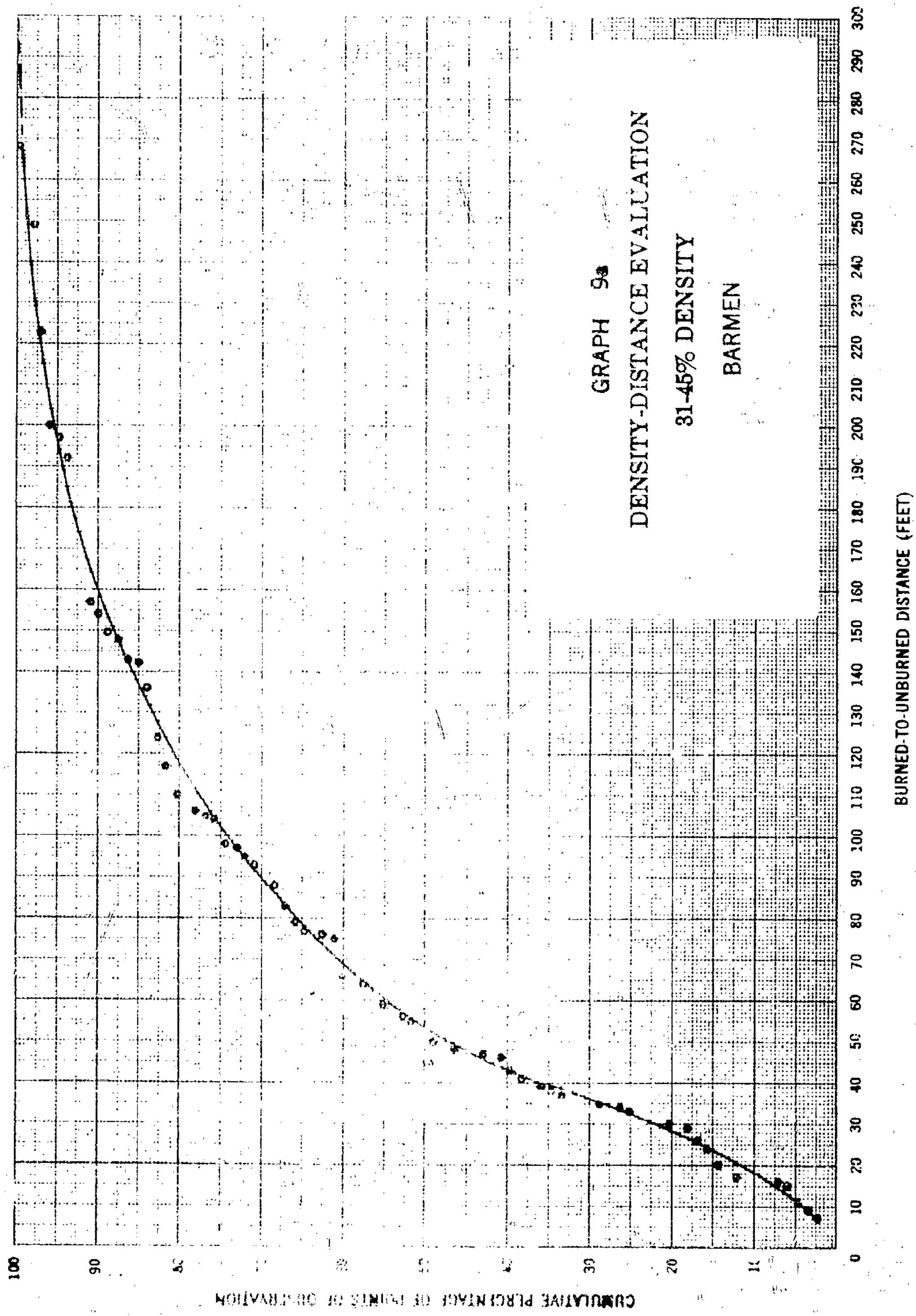
The German cities of Elberfeld, Barmen, and Darmstadt and the Japanese city of Kure were selected for this study. It will be recalled that, in the investigation to find the relationship between building densities on each side of the burn line (Test I), bands 400 feet deep on each side were used as a basis. The practicability of using this same measurement in an attempt to establish a density-distance relationship at the burn line was questioned. The 400-foot bands had been set following mere visual examination of the pre- and post-attack photography, but after measuring distances between burned and unburned buildings, it appeared that a distance of 300 feet was probably sufficient to stop the spread of fire in nearly every case. Therefore, a band 300 feet in depth was established inside the burn line of each city and divided into sections with homogeneous building density and pattern. Building density readings were taken for each section, and the burned-to-unburned distances were measured for all points of observation along the burn line (see Illustration 11). Curves were plotted showing the cumulative percentage of points where the fire was stopped at increasing distances between buildings within building density ranges of 15 per cent (see Graphs 9a,b,c; 10a,b; 11a,b; and 12a,b,c). For purpose of comparison, these curves were then transferred to tabular form (see Table III). For this test, curves were not drawn for density ranges with 25 points of observation or less.

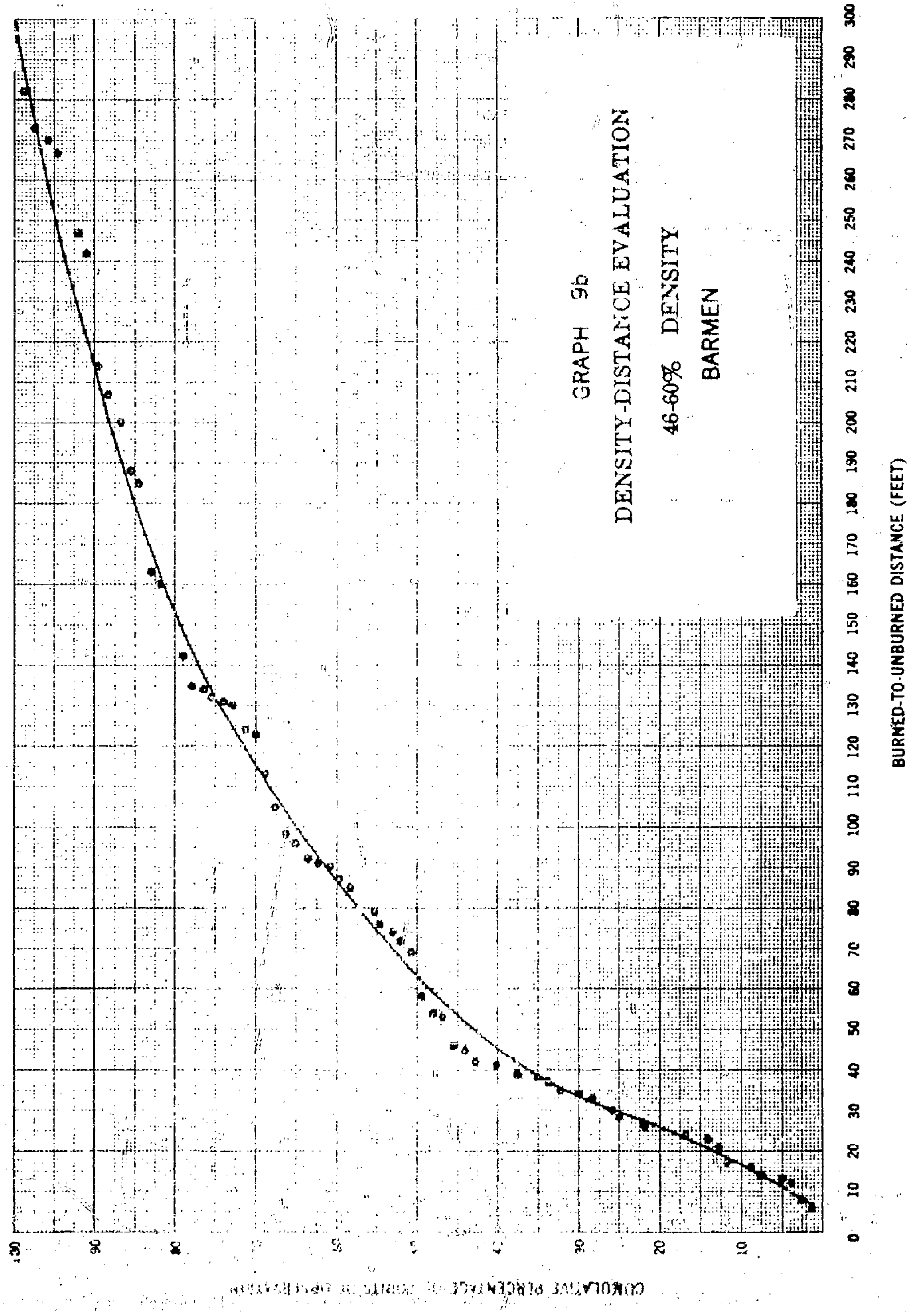
Comparison of the data for the German cities disclosed that the percentage of observed burned-to-unburned distances generally did not increase with an increase in building density, which is contrary to what had been anticipated. There also were inconsistencies between the 46-60 per cent and the 61-75 per cent building density ranges in Kure. Although the building density in Kure was much higher than in the German cities, a larger percentage of the points observed were of short burned-to-unburned distance in the Japanese city. This reaffirmed the importance of type of construction and fire load to burning time and, consequently, to probability of fire spread.

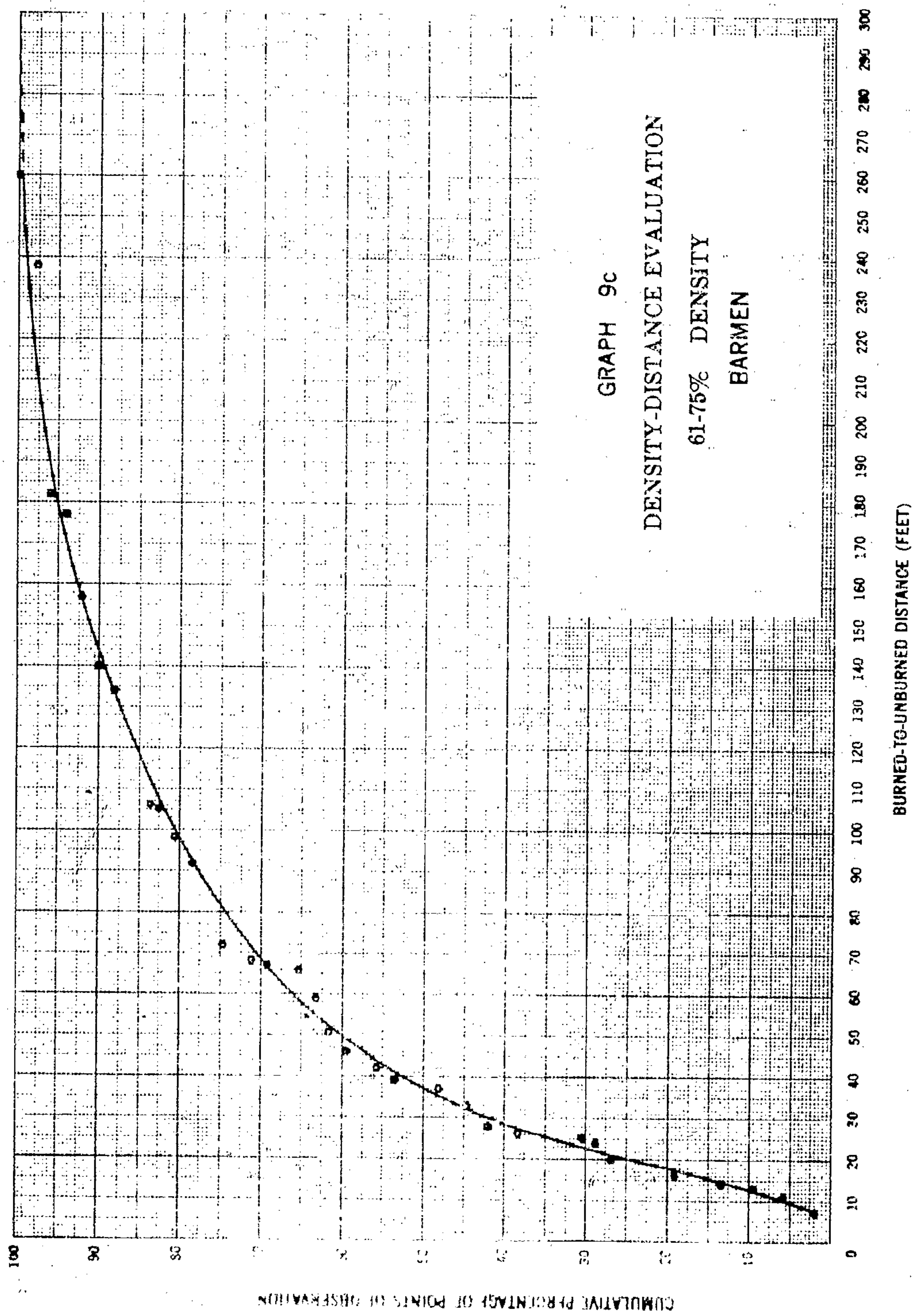
The unexpected results in the density-distance analysis for the German cities indicated that building density by itself is not a satisfactory measure of the fire load of buildings and contents. There was reason to believe that building volume, which reflects both building density and height, might prove to be a better measure of fire load in a built-up area than building density alone. Therefore, it was decided to investigate next the effect of building volume on the distance required to stop spread of fire at the fire perimeter.

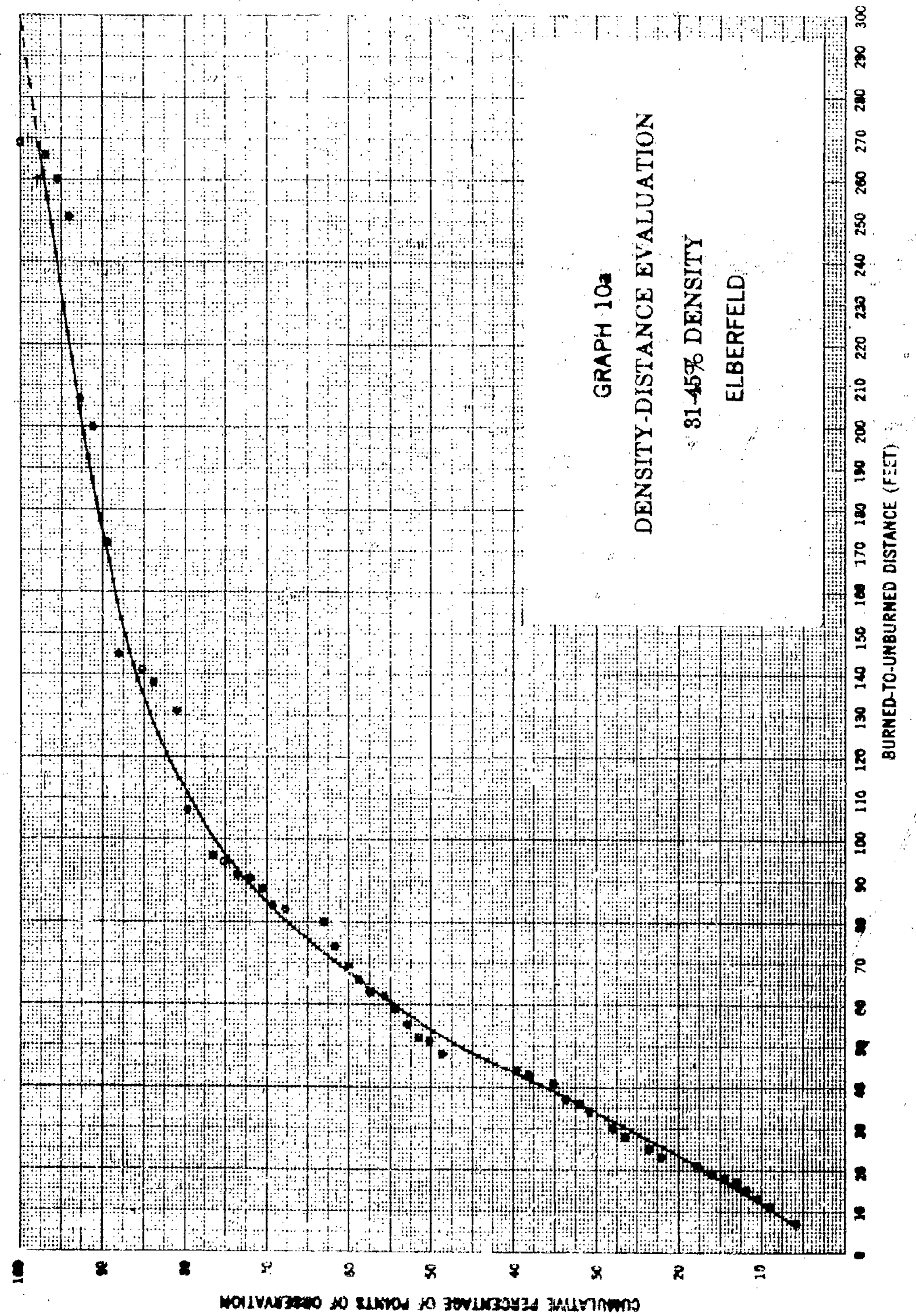
D. TEST IV - Volume-Distance Evaluation

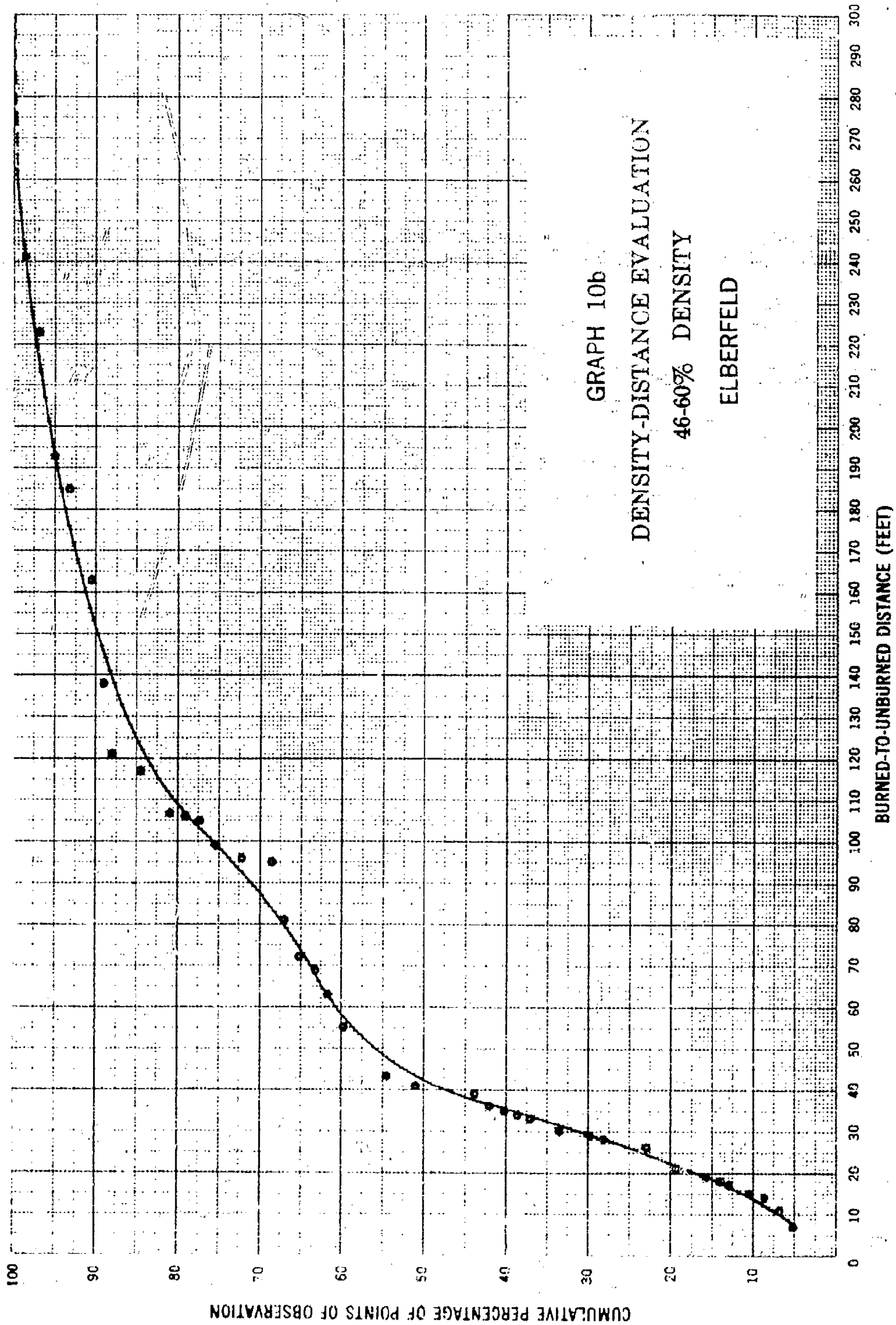
Two methods of analysis were used in the volume-distance evaluation. In the first analysis, a study was made of the relationship of the volume of individual burned buildings directly facing unburned buildings at the fire perimeter and the distances between them. The cities of Darmstadt,

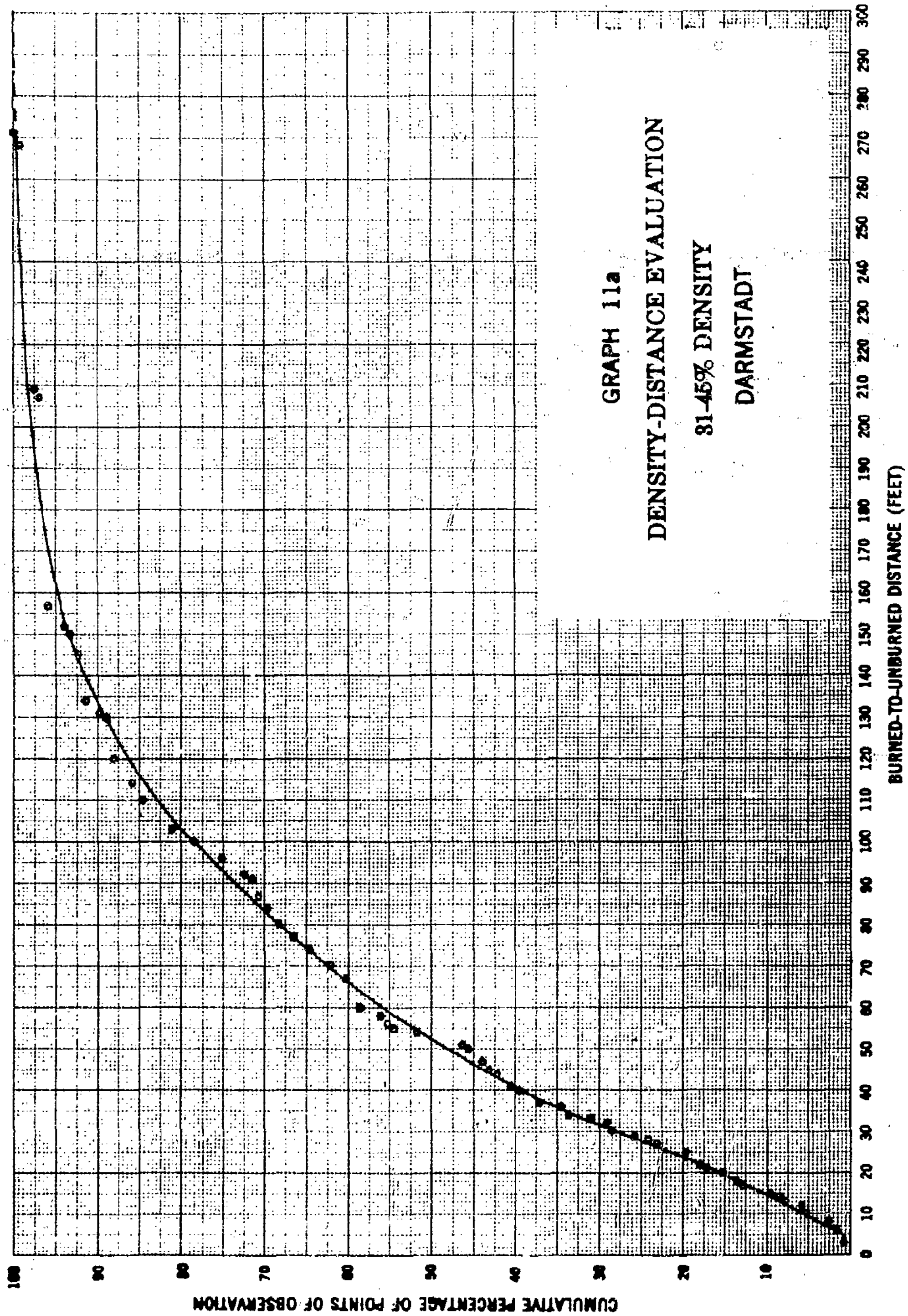

GRAPH 9a
DENSITY-DISTANCE EVALUATION
31-45% DENSITY
BARMEN
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION

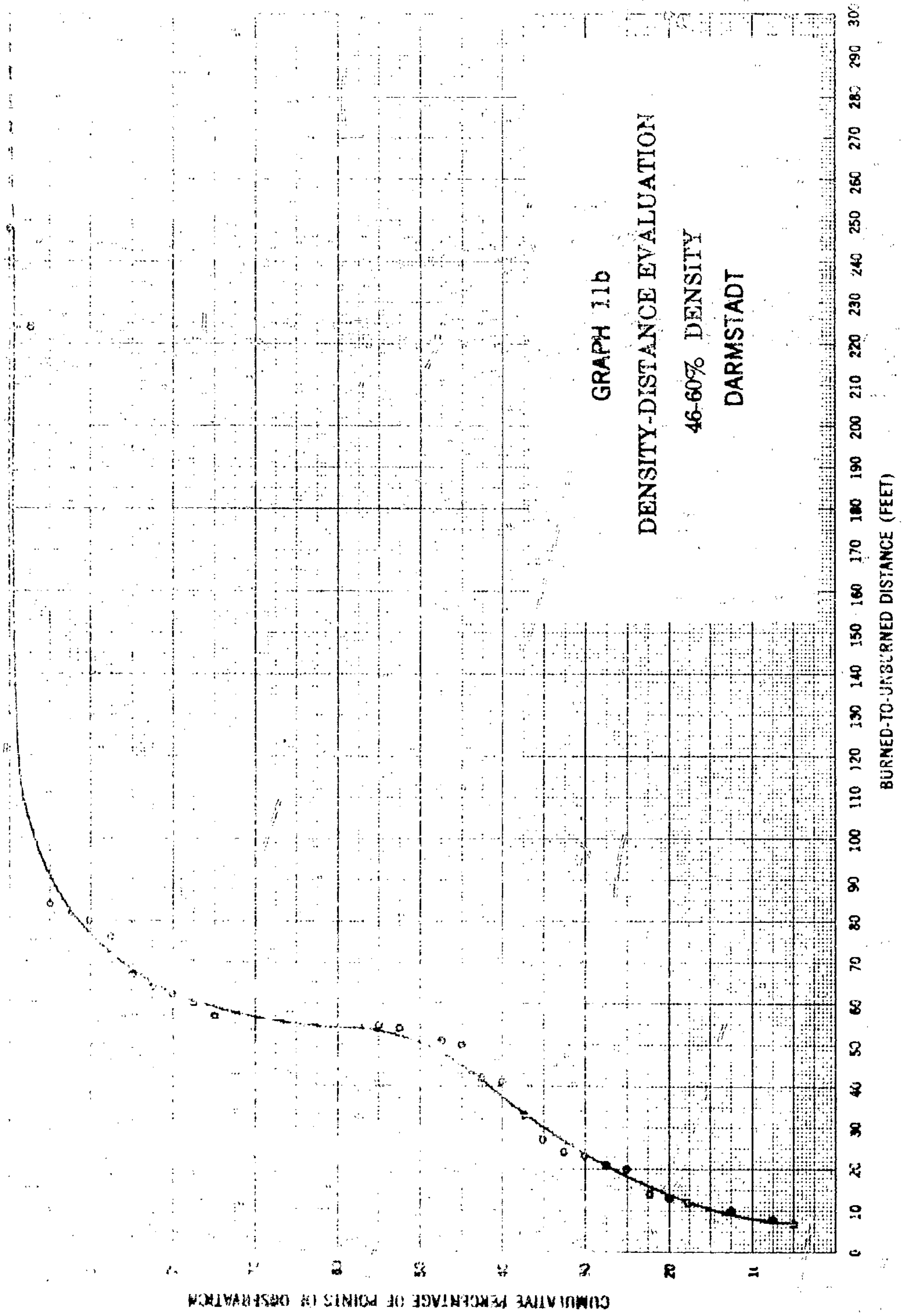

GRAPH 9b
DENSITY-DISTANCE EVALUATION
46-60% DENSITY
BARMEN
BURNED-TO-UNBURNED DISTANCE (FEET)

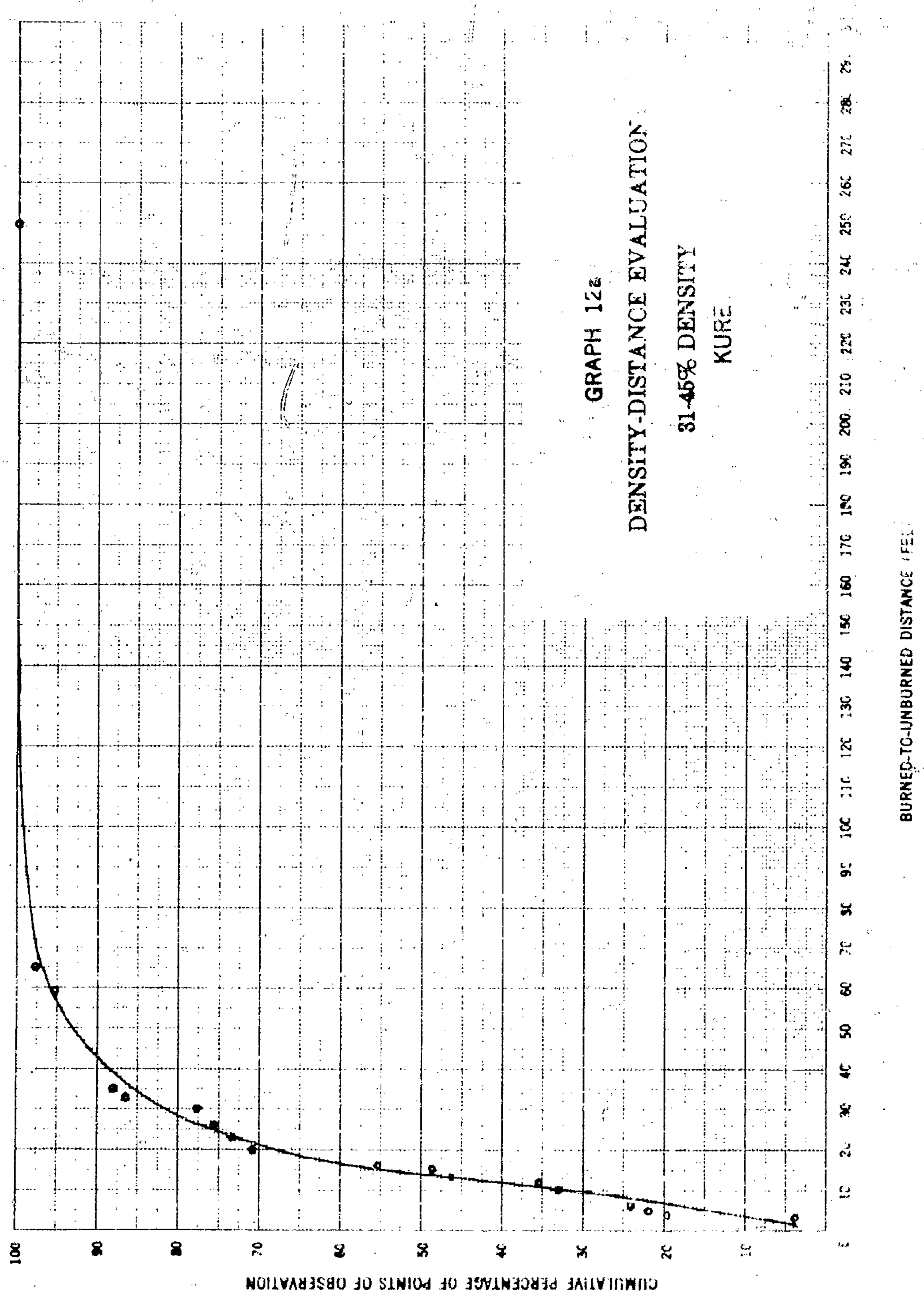

GRAPH 9c
DENSITY-DISTANCE EVALUATION
61-75% DENSITY
BARMEN
BURNED-TO-UNBURNED DISTANCE (FEET)

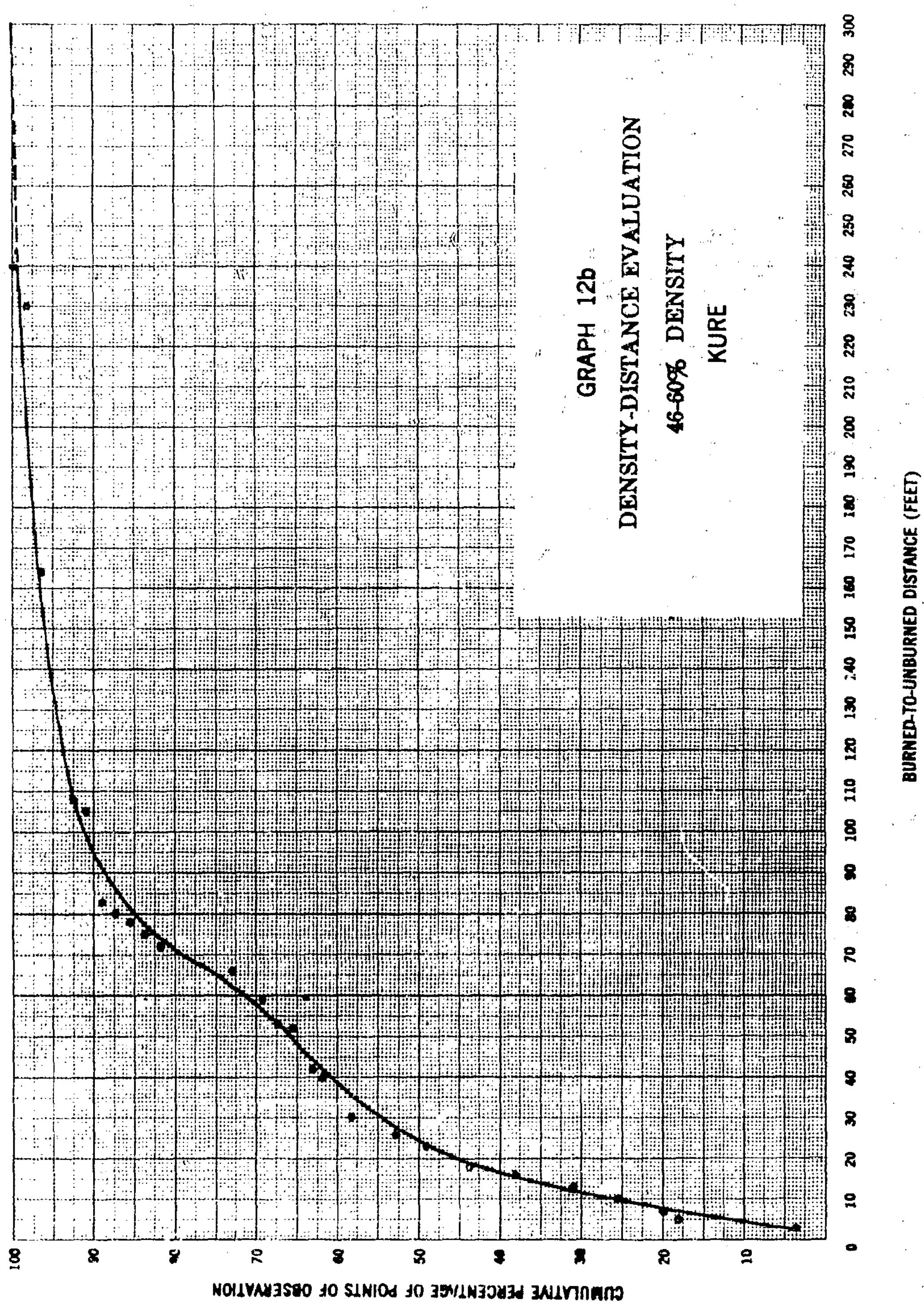

GRAPH 10a
DENSITY-DISTANCE EVALUATION
31-45% DENSITY
ELBERFELD
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 10b
DENSITY-DISTANCE EVALUATION
46-60% DENSITY
ELBERFELD
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 11a
DENSITY-DISTANCE EVALUATION
31-45% DENSITY
DARMSTADT
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 11b
DENSITY-DISTANCE EVALUATION
46-60% DENSITY
DARMSTADT
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 12a
DENSITY-DISTANCE EVALUATION
31-45% DENSITY
KURE
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 12b
DENSITY-DISTANCE EVALUATION
46-60% DENSITY
KURE
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION

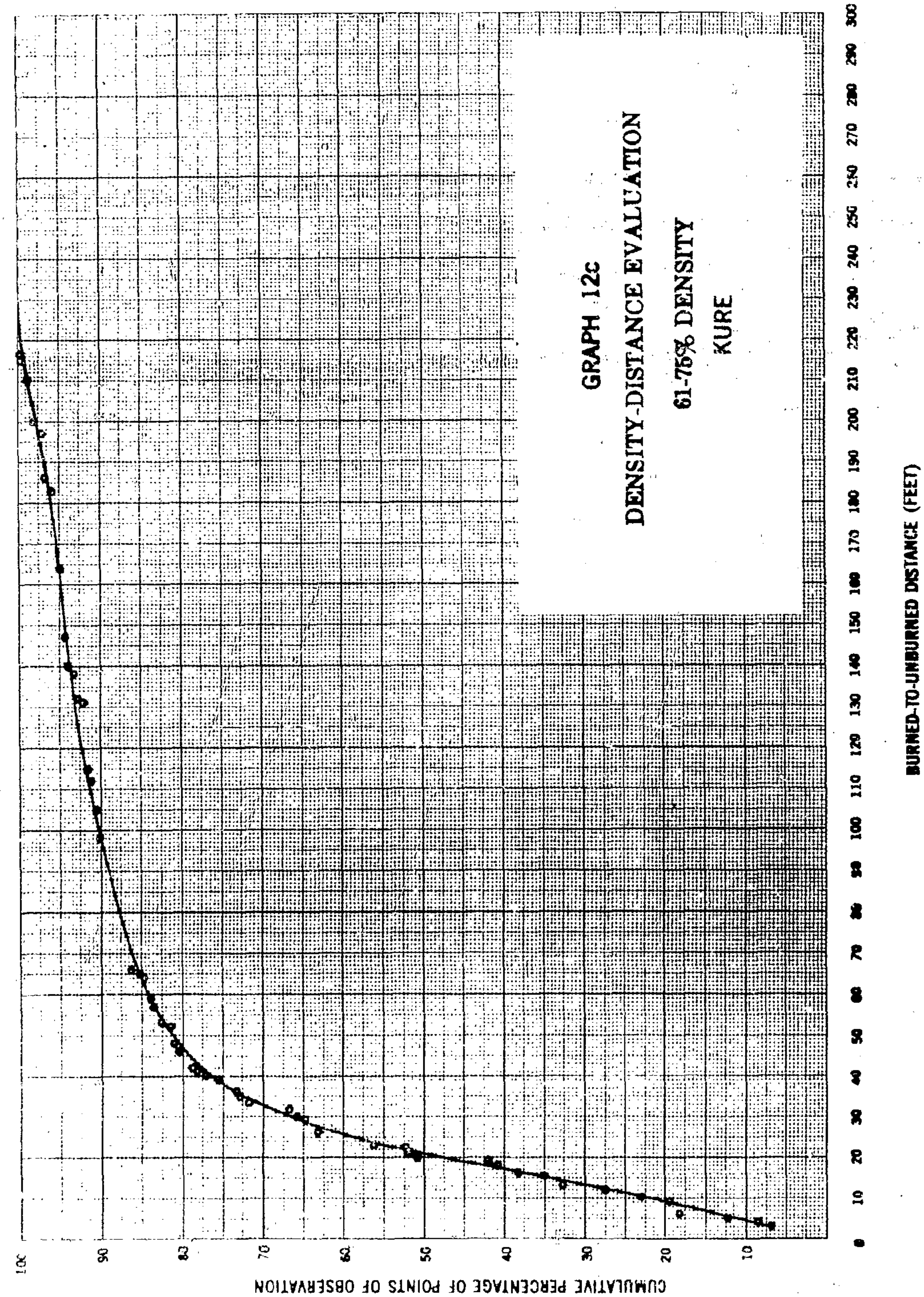

GRAPH 12c
DENSITY-DISTANCE EVALUATION
61-75% DENSITY
KURE
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION

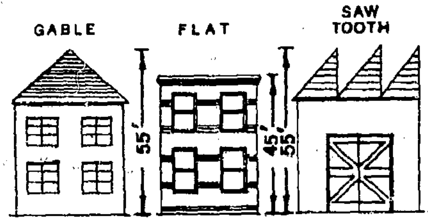
TABLE III

DENSITY-DISTANCE EVALUATION

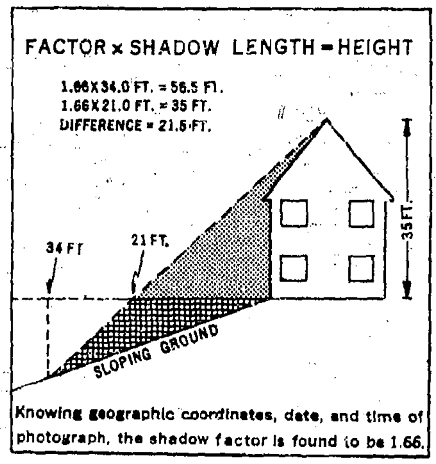
Burned-to Unburned Distance (in Feet)	Cumulative Percentage of Points of Observation at which Fire Stopped in Each Density Range									
	BARMEN			ELBERFELD		DARMSTADT		KURE		
	31-45%	46-60%	61-75%	31-45%	46-60%	31-45%	46-60%	31-45%	46-60%	61-75%
10	3.5	4.0	5.5	8.5	6.5	5.5	14.0	31.0	26.0	21.5
20	11.5	13.0	24.5	16.5	17.0	15.5	26.5	68.0	45.0	47.0
30	21.5	25.5	42.0	26.0	31.0	28.0	35.0	81.5	54.5	66.5
40	30.5	36.0	52.5	36.0	47.0	39.0	41.5	88.5	60.5	76.5
50	47.0	43.0	60.0	46.5	56.0	48.0	49.5	93.0	65.5	81.5
60	54.5	48.5	66.0	54.5	60.5	55.5	76.5	96.0	71.5	84.0
70	60.5	53.0	70.5	61.5	64.0	62.5	86.5	97.5	79.0	86.0
80	66.0	57.5	74.5	67.5	67.5	68.0	91.5	98.3	85.0	87.5
90	70.5	61.0	77.5	72.5	71.0	73.5	94.5	98.8	88.5	89.0
100	74.0	65.0	80.5	76.5	75.5	78.5	97.0	99.2	91.0	90.2
110	77.5	68.5	83.0	79.5	80.5	83.0	98.5	99.5	92.5	91.5
120	80.5	71.5	85.5	82.0	84.0	86.0	99.0	99.6	93.5	92.2
130	83.5	74.5	87.5	84.0	86.5	89.0	99.2	99.7	94.5	93.0
140	86.0	77.0	89.0	86.0	88.0	91.5	99.4	99.8	95.5	93.7
150	88.0	79.5	91.0	87.5	89.5	93.5	99.5	99.9	96.0	94.3
300	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. of Points of Observation:	84	77	52	68	57	116	40	45	55	186
Graph Number	9a	9b	9c	10a	10b	11a	11b	12a	12b	12c

Barmen, and Kure were selected for study so that the burned-to-unburned distance measurements made in Test III could be used. Therefore, it was necessary to measure only the length, depth, and height of each burned building opposite an unburned building in order to calculate its volume.

The true height of a building was considered as the distance from the ground to the top or peak of the roof (see Illustration 12). A sufficiently accurate method of calculating heights with the photography available had to be found. Two methods were available, namely, the shadow-factor method and the height parallax method. 1/ Many calculations were made by the shadow-factor method, and it was found to be accurate within the limits required (to the nearest five feet) when measuring buildings on level ground; however, major discrepancies were evident when buildings at the top or on the side of a slope were measured (see Illustration 13). This method was eventually discarded in favor of the height parallax method which was found to be accurate under nearly all conditions.



ILLUST. 12 HEIGHTS MEASUREMENTS



ILLUST. 13 HEIGHT ERROR USING SHADOW FACTOR

Since some of the photography for Darmstadt was of poorer quality than that for the other cities, a ground check of that city was made through arrangements made by the Directorate of Intelligence, Headquarters USAF. This ground check showed that, despite the poor quality of the photography, 90 per cent of the heights calculated by the height parallax method were correct within plus or minus five feet, many buildings were exactly the same height as calculated, and the errors in the remaining 10 per cent were slight.

Throughout the extended period that was required to measure building heights on photographs, information on actual heights of buildings in the cities under study was sought, especially in the collections of the Library of Congress, for purposes of verification. However, only limited information of the type required was available. Actual heights of numerous church steeples and towers were found, but these were of no value because the heights were excessive, and split parallax or distortion made it impossible to measure such structures on photographs.

Once the volume was calculated for each burned building facing an unburned building at the fire perimeter, it was tabulated against the

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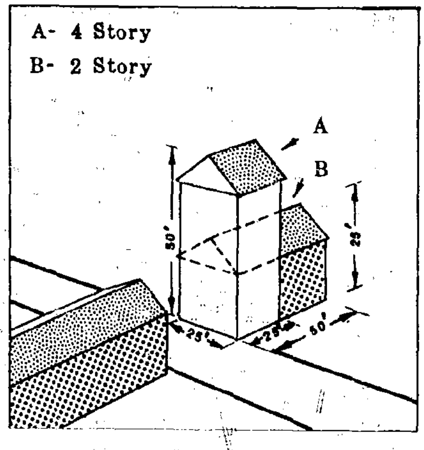
1/ Interim Photographic Interpretation Handbook, NAVAER 10-35-500, U.S. Naval Photographic Interpretation Center, Washington, 1949, Section 9.

distance between the two buildings. Although the collected data, particularly for Kure, showed some indication that increasing distances are required to stop fire spread with increasing volume of individual burned buildings, no consistent correlation was demonstrated. Perhaps one reason for inconsistencies noted in the results is the fact that buildings of the same volume may have considerably different heights and areas of exposure face (see Illustration 14), the effect of which is not reflected by a simple volume-distance analysis. Another likely reason for the inconsistencies is that, in a mass fire, the amount of radiated heat received by an exposed building at the fire perimeter probably depends more upon the volume of burning buildings in an area of some length and depth, rather than upon the volume of an individual building facing it.



ILLUST. 14 TWO AND FOUR STORY BUILDINGS WITH SAME VOLUME

In the second analysis in the volume-distance evaluation, a study was made of the relationship of the volume of burned buildings within sections of homogeneous building density along the fire perimeter and the distances to unburned buildings outside the fire perimeter. The cities of Hamburg, Barmen, and Kure were selected for this analysis.

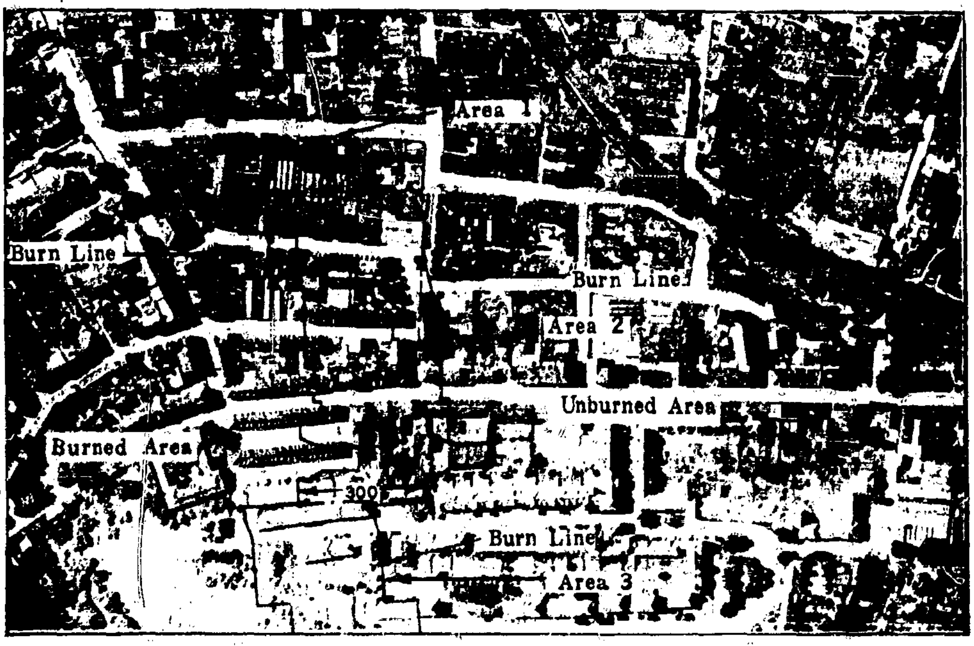
A method of photographic analysis was evolved to obtain the necessary data. Three overlays were prepared for each city. The first overlay showed a band 300 feet in depth inside the line of burn with this band divided into sections that were homogeneous in building density pattern (see Illustration 15a), the second overlay showed the distances from burned to unburned buildings at all points of observation along the burn line (see Illustration 15b), and the third overlay showed the heights of all buildings within the 300-foot band (see Illustration 15c).

Data were compiled showing the total volume of buildings within each homogeneous section and the distance from burned to unburned buildings. To establish a uniform measure of volume, calculations were made to express the volume of each homogeneous section as a "unit volume", i.e., in terms of cubic feet per 100 feet of fire perimeter of the section, or cubic feet per 30,000 square feet of ground area (100-feet of fire perimeter multiplied by 300-foot depth of section). In this case the length of the fire perimeter was taken to be the length of the section, which was measured along a straight line approximating the principal direction of the fire perimeter of the section. The average height of each homogeneous section was calculated by dividing the total cubic feet of buildings in the section by the total square feet of plan area of the buildings.

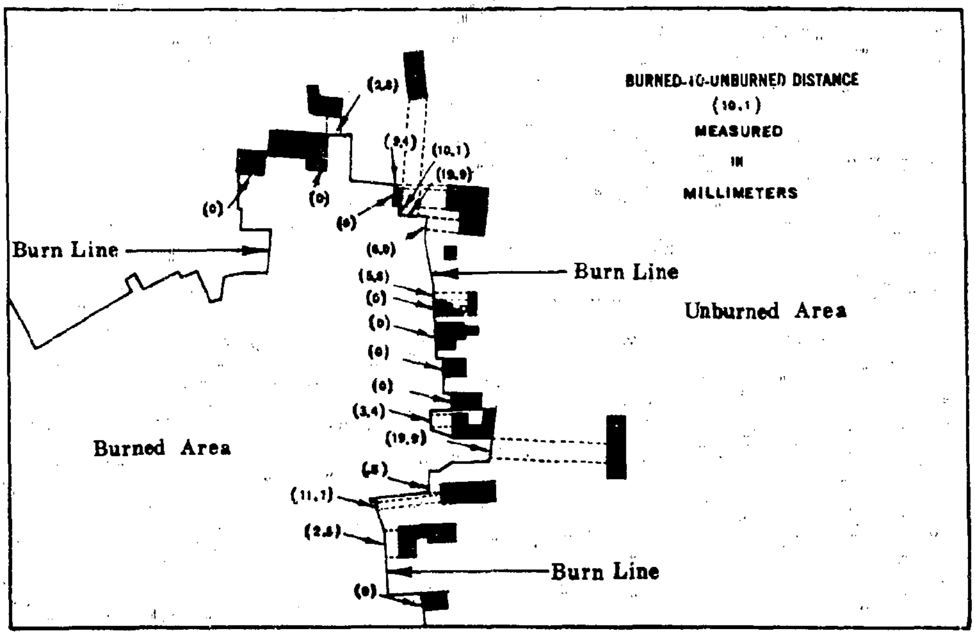
A wide variation in unit volumes was found within the three cities selected for study. Therefore, it was necessary to establish suitable groupings into which these unit volumes could be placed, so that

curves for cumulative points-of-observation versus corresponding burned-to-unburned distances could be plotted for various unit volume groups. It was expected that as unit volumes increased, burned-to-unburned distances would also increase.

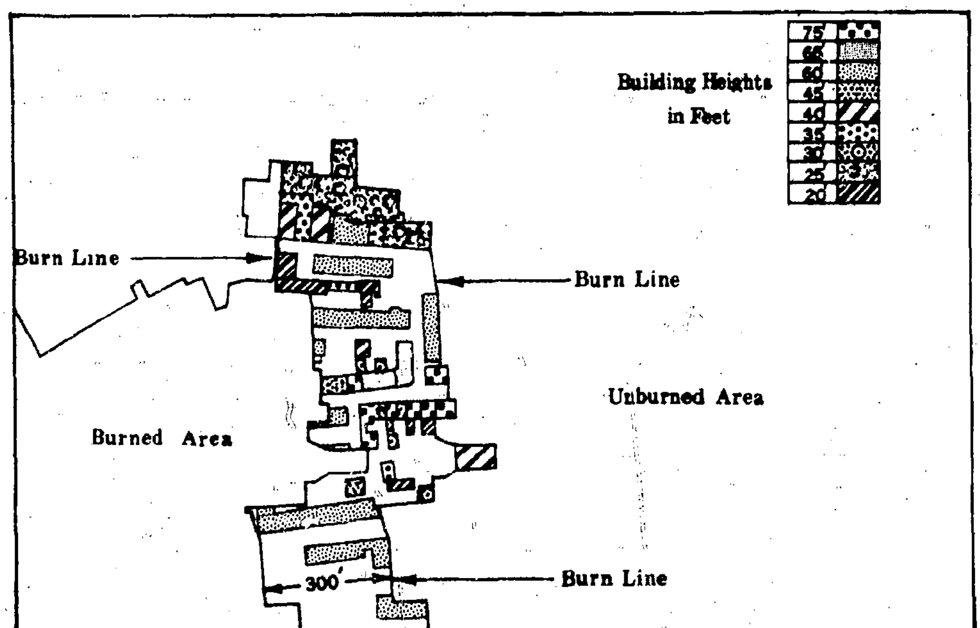
One set of volume groupings was established by multiplying 30,000 square feet (ground area, 100 feet by 300 feet) by various building densities (in 10 per cent increments beginning with 5 per cent), and by a building height constant (taken as 30 feet, the average height of two-story buildings). However, when the unit volumes obtained in the volume-distance study for Kure were combined according to this set of groupings, it was found that there were insufficient points of observation within each volume group to produce satisfactory curves. Therefore, this set of volume groupings was discarded and the search for a more suitable set was continued. Finally, an apparently suitable set of volume groupings was established by multiplying 30,000 square feet (ground area, 100 feet by 300 feet) by a building density constant (taken as 40 per cent, the average building density in Hamburg and Barmen) and by various building heights (in 10-foot increments beginning with 5 feet, assuming the first story of a building to be 15 feet and each additional story, 10 feet).



ILLUST. 15a AREA DIVIDED INTO HOMOGENEOUS SECTIONS (300 FT. BAND)



ILLUST. 15b BURNED-TO-UNBURNED DISTANCES OR POINTS OF OBSERVATION



ILLUST. 15c BUILDING HEIGHTS WITHIN 300-FOOT BAND

For each volume group, curves for cumulative points-of-observation versus corresponding burned-to-unburned distances were developed for each of the cities of Hamburg, Barmen, and Kure (see Graphs 13a,b,c,d; 14a,b,c; and 15a,b,c). For purpose of comparison, these curves were then transferred to tabular form (see Table IV).

The results for each of the two German cities showed no correlation between different volume groups in the same city, and, although both cities had essentially the same kind of construction and occupancy, there was considerable variance between the results for the same volume groups in the two cities. After careful examination of the photography and other available data, it was thought that the differences might have resulted from accumulating data purely on the basis of volume without regard to the fact that a wide variety of building density and height combinations produced equal volumes. This was supported by the results for Kure, where the building densities and heights in the same volume group did not vary widely. In that city, fairly good correlation between different volume groups was obtained, that is, distances between burned and unburned buildings generally increased with increases in volume.

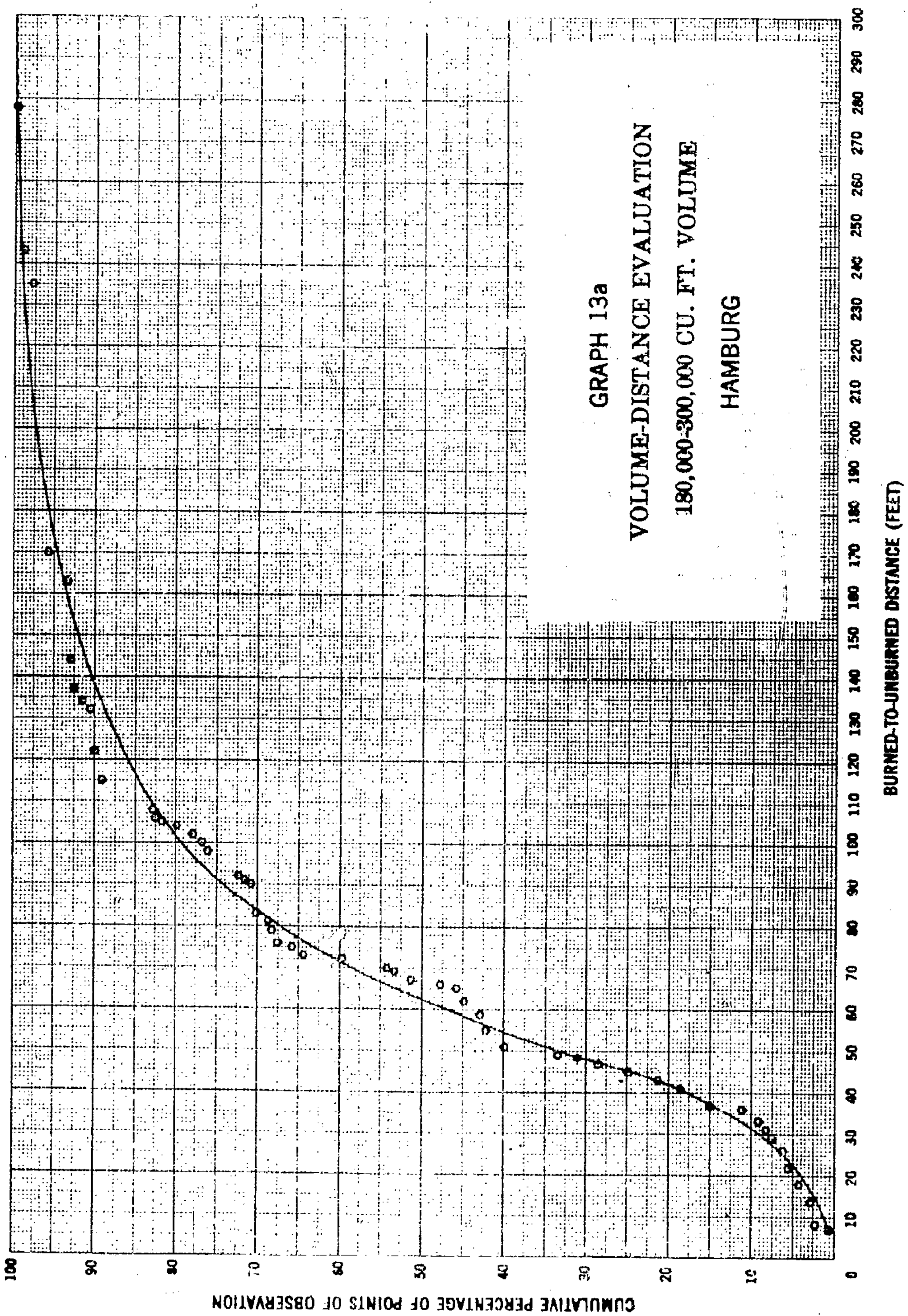
Comparison of the Kure graphs with those for Hamburg and Barmen shows that for all volume groups much shorter distances were required to stop fire in Kure. This confirmed the conclusion reached at the completion of Test II that curves developed for German cities would not be consistent with those developed for Japanese cities because of the generally lower building heights and lighter combustible building materials and contents in the Japanese cities.

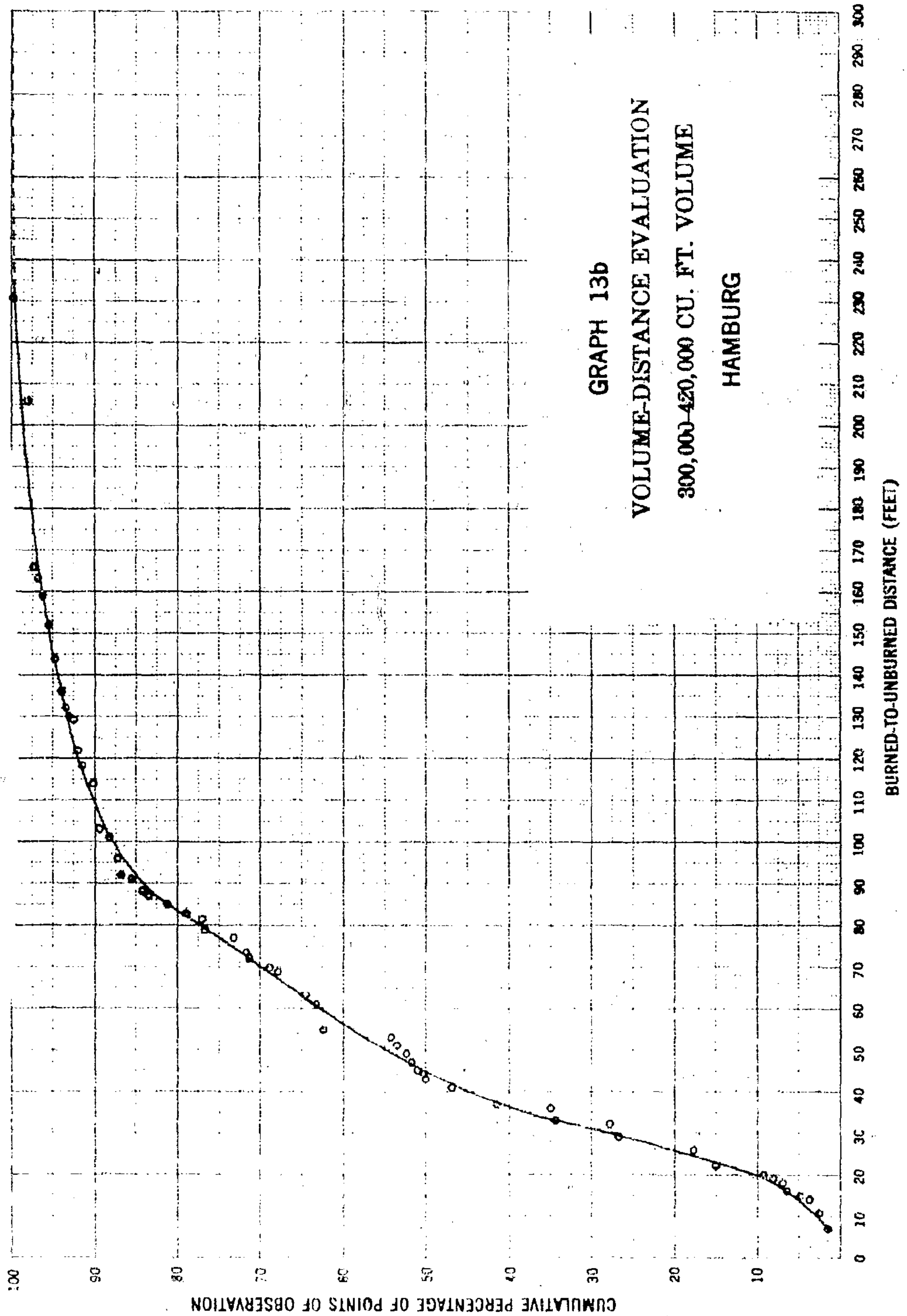
Because of the fairly good correlation obtained between the curves for different volume groups in the Kure analysis, it appeared likely that, if building densities and heights are fairly uniform, curves plotted for cumulative points-of-observation versus corresponding burned-to-unburned distances would show reasonable consistency. Therefore, it was decided to develop such curves for various combinations of building densities and heights in German cities and in Japanese cities. It was also decided to consolidate all the German data, and all the Japanese data, in order to obtain an adequate number of observations in each density-height combination for each of the two types of construction, and to obtain an average of the effects of differences in physical and structural factors in the individual cities.

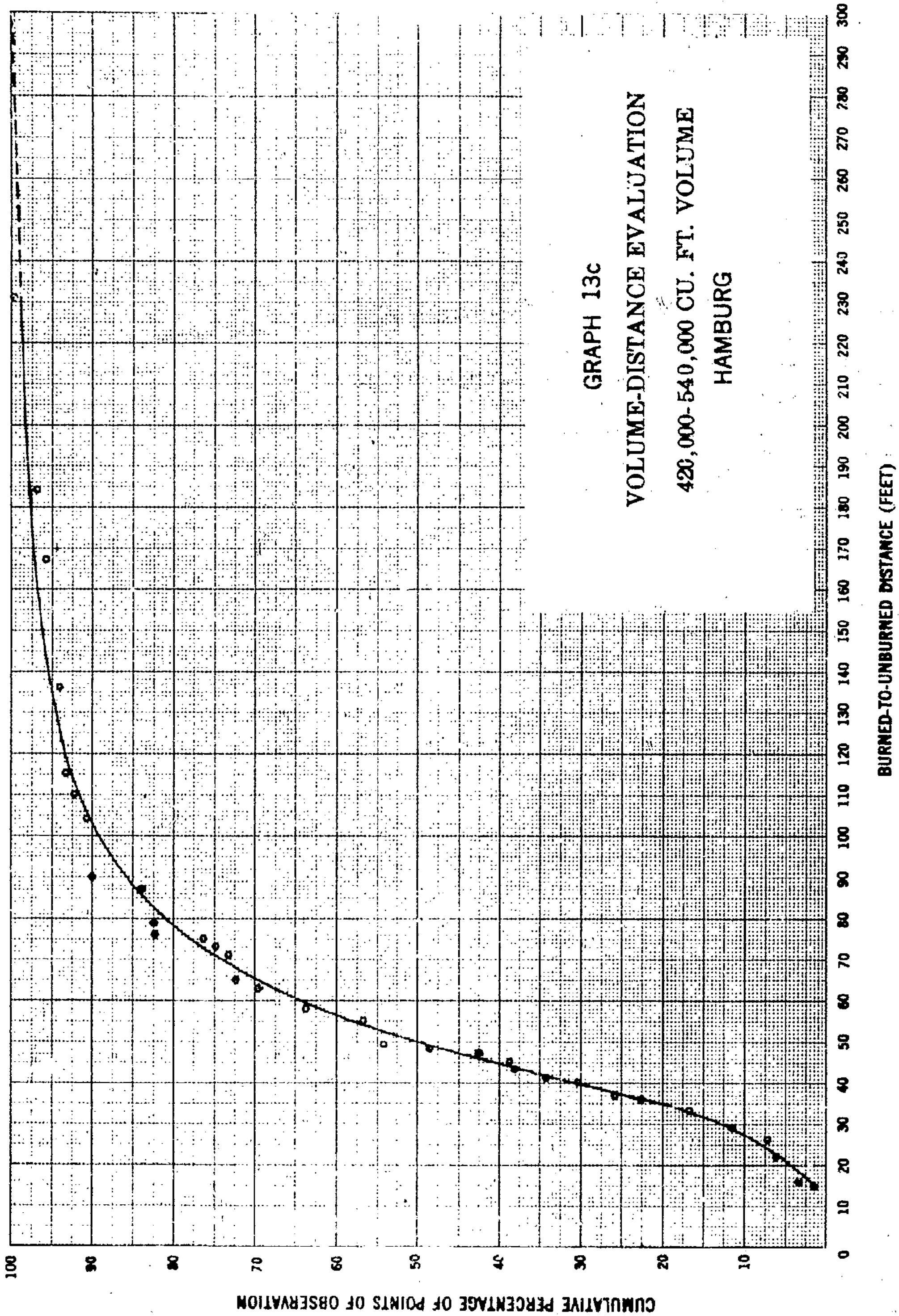
E. <u>TEST V - Density-Height-Distance Evaluation</u>

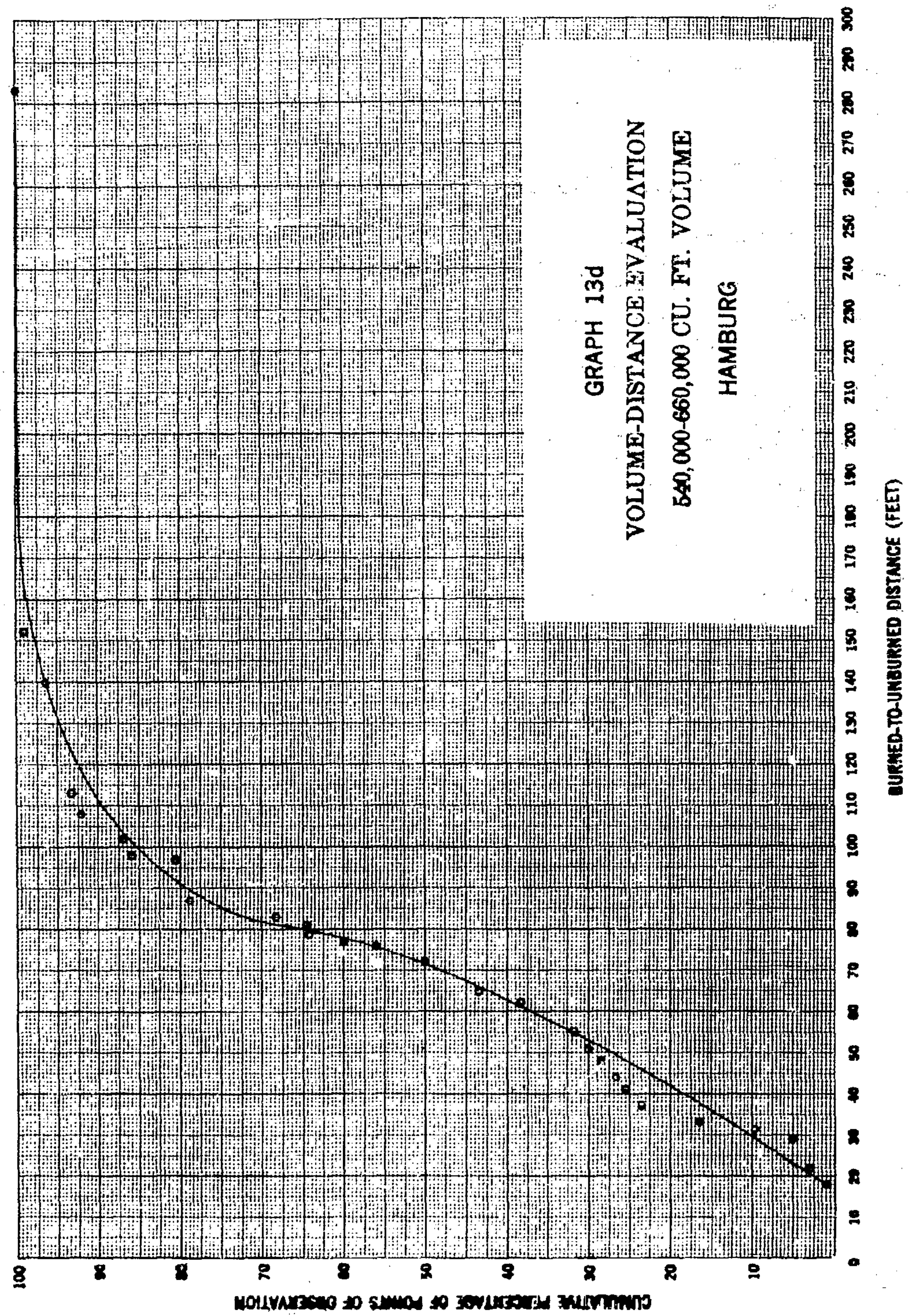
Photographic analyses were made of the additional German cities of Elberfeld, Darmstadt, Kassel, and Essen, and of the Japanese cities of Hiroshima, Nagasaki, and Sakai, similar to the analyses made of Hamburg, Barmen, and Kure in Test IV.

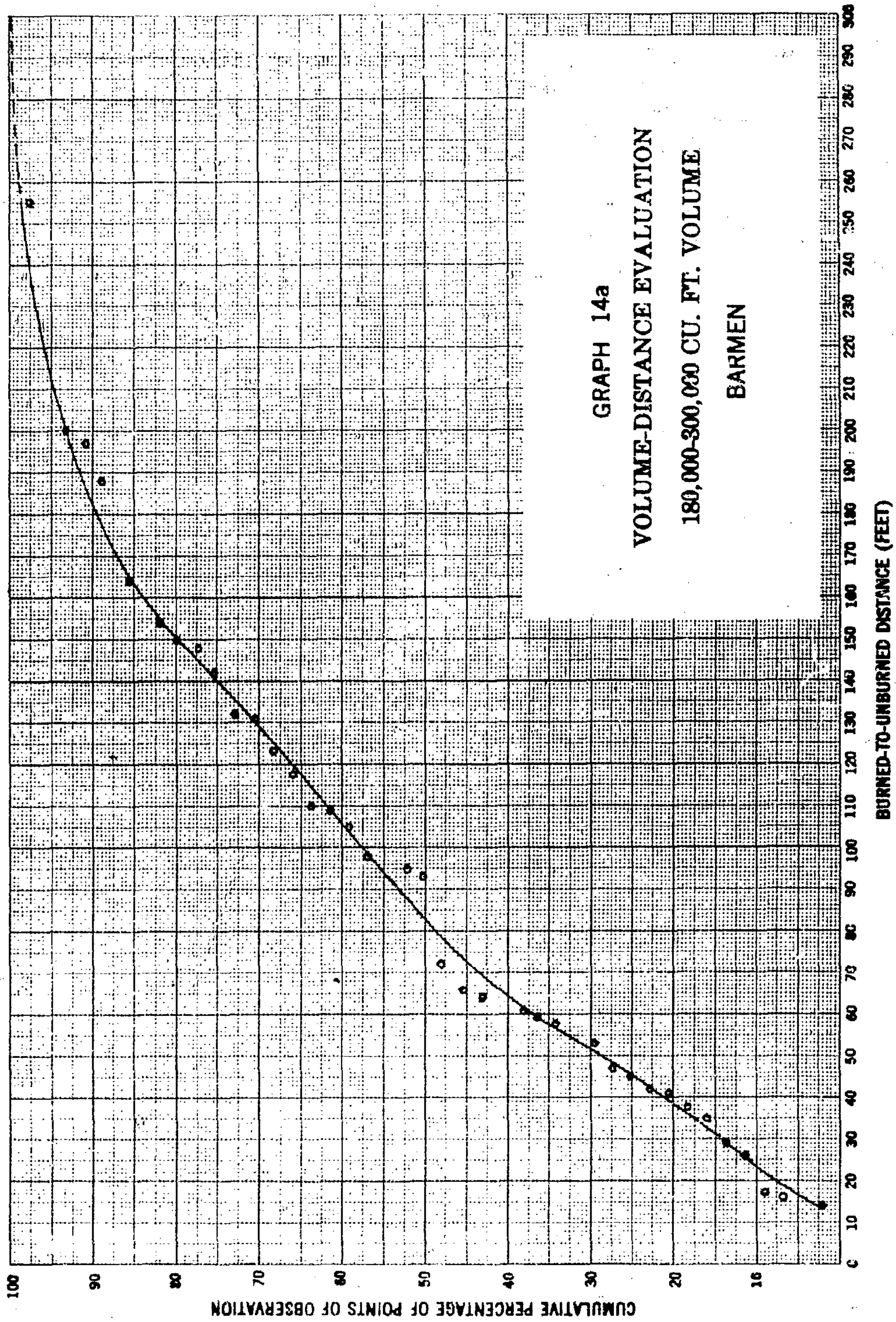
Hiroshima and Nagasaki were selected in order to see what comparison could be made between the spread of fire after atomic attack on these cities and after conventional attack on Kure and Sakai. It was also desired to develop data for Hiroshima by photographic analysis so that the results could be compared subsequently with the fire spread probability versus distance curve in the U.S.S.B.S. report for that city (see Graph 3).

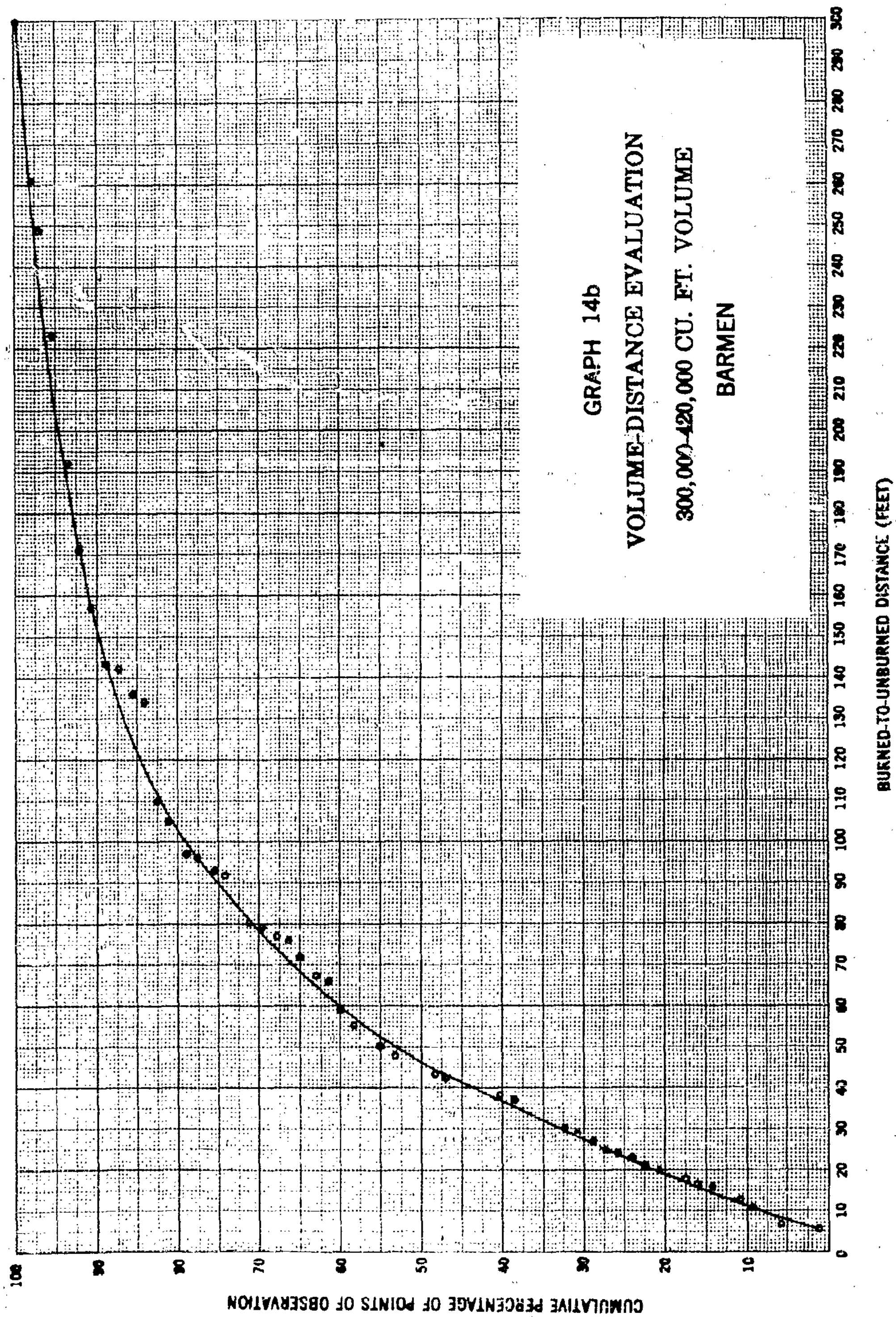

GRAPH 13a
VOLUME-DISTANCE EVALUATION
180,000-300,000 CU. FT. VOLUME
HAMBURG
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION

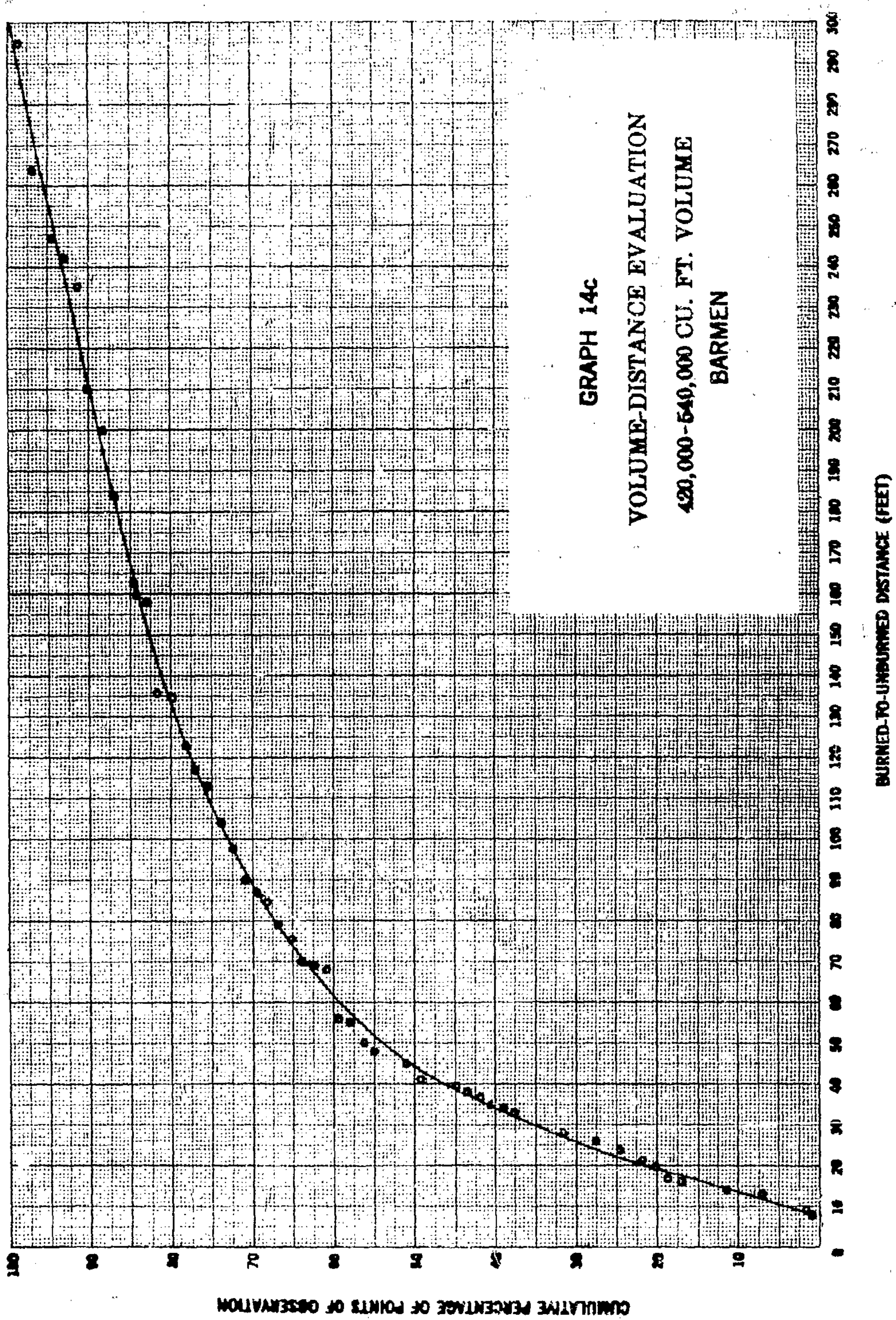

GRAPH 13b
VOLUME-DISTANCE EVALUATION
300,000-420,000 CU. FT. VOLUME
HAMBURG
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300

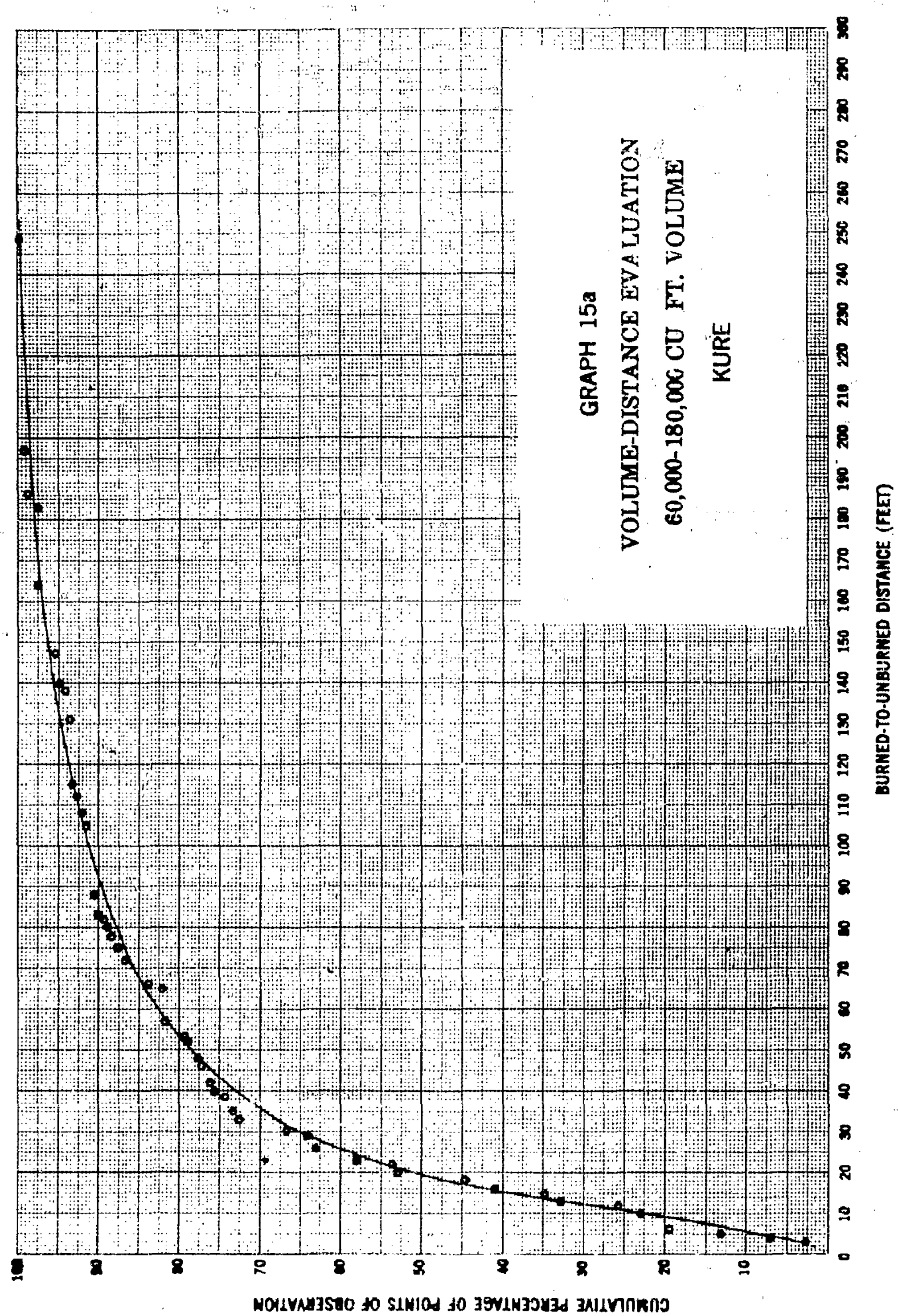

GRAPH 13c
VOLUME-DISTANCE EVALUATION
420,000-540,000 CU. FT. VOLUME
HAMBURG
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300

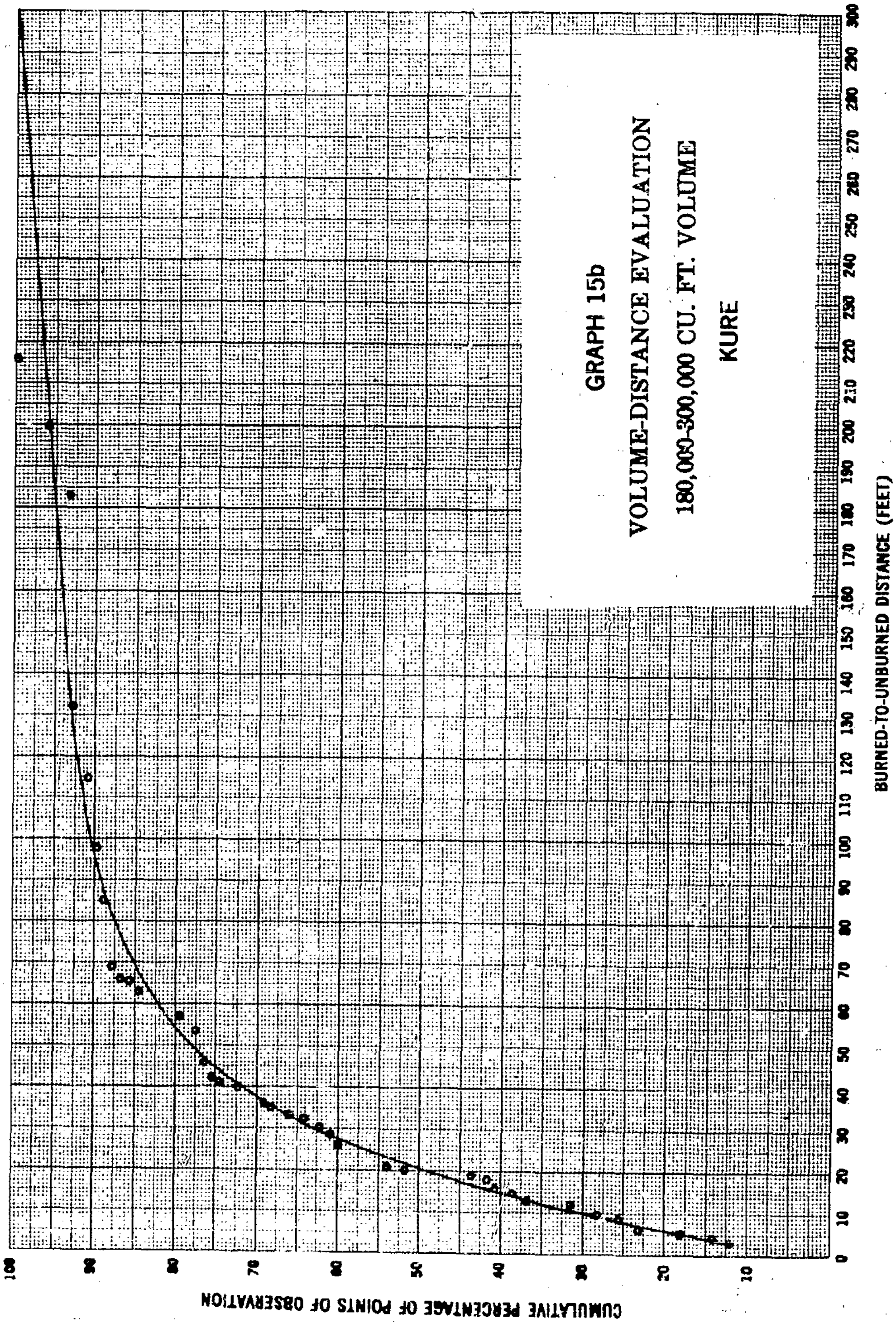

GRAPH 13d
VOLUME-DISTANCE EVALUATION
540,000-660,000 CU. FT. VOLUME
HAMBURG
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 14a
VOLUME-DISTANCE EVALUATION
180,000-300,000 CU. FT. VOLUME
BARMEN
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 14b
VOLUME-DISTANCE EVALUATION
300,000-420,000 CU. FT. VOLUME
BARMEN
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 14c
VOLUME-DISTANCE EVALUATION
420,000-540,000 CU. FT. VOLUME
BARMEN
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 15a
VOLUME-DISTANCE EVALUATION
60,000-180,000 CU FT. VOLUME
KURE
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 15b
VOLUME-DISTANCE EVALUATION
180,000-300,000 CU. FT. VOLUME
KURE
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION

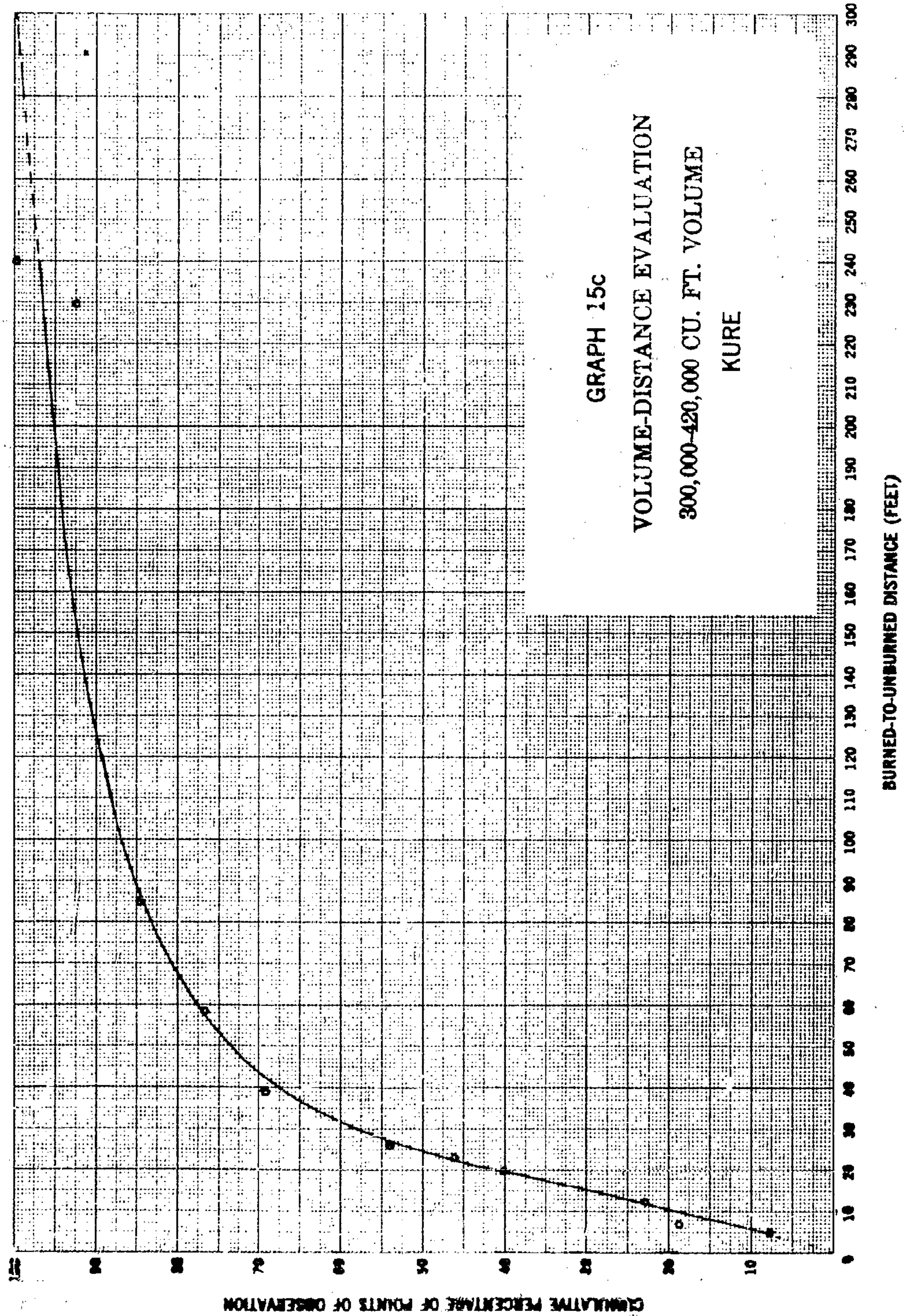

GRAPH 15c
VOLUME-DISTANCE EVALUATION
300,000-420,000 CU. FT. VOLUME
KURE
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION

TABLE IV

VOLUME-DISTANCE EVALUATION

Burned-to-Unburned Distance (in Feet)	Cumulative Percentage of Points of Observation at which Fire Stopped in Each Volume Group*									
	HAMBURG				BARMEN			KURE		
	2*	3*	4*	5*	2*	3*	4*	1*	2*	3*
10	1%	3%	-%	-%	-%	8%	4%	22%	30%	19%
20	4	10	4	3	8	21	22	51	50	41
30	9	27	12	10	14	33	35	65	63	58
40	18	45	30	18	21	44	46	73	72	68
50	33	55	50	27	29	53	54	79	78	74
60	47	63	64	37	36	60	59	83	82	78
70	58	70	74	48	43	66	64	86	85	81
80	67	77	81	65	49	71	67	88	87	83
90	74	84	86	79	53	75	70	90	89	85
100	79	88	89	85	57	79	73	91	90	87
110	83	90	92	89	62	82	75	93	91	88
120	86	92	93	92	66	85	77	94	92	89
130	88	93	94	94	70	87	79	95	93	90
140	90	94	95	96	75	89	81	96	93	91
150	92	95	96	98	80	90	83	96	94	92
300	100	100	100	100	100	100	100	100	100	100
Number of Points of Observation:	75	112	59	33	44	62	69	181	98	13
Graph Number	13a	13b	13c	13d	14a	14b	14c	15a	15b	15c

* Group No.	Volume (cu.ft.)
1	60,000-180,000
2	180,000-300,000
3	300,000-420,000
4	420,000-540,000
5	540,000-660,000

For each city, and for each homogeneous section within the 300-foot band inside the fire perimeter, data were obtained by measurement or calculation and tabulated 1/ under the following headings: building density (per cent), volume (cu.ft.), length of fire perimeter (ft.), unit volume (cu.ft. per 100 ft. of fire perimeter), average height (ft.), distance from burned building to unburned building (ft.) for each point of observation, and length of radiation face (ft.) for each observation. Data which had been developed in previous tests were used, insofar as possible, in making the tabulations. The volume, fire perimeter, unit volume, and average height measurements and calculations were made in the same way as described in the second volume-distance analysis in Test IV.

Cumulative points-of-observation curves versus corresponding burned-to-unburned distances were drawn for the combined data for the six German cities (Hamburg, Barmen, Elberfeld, Darmstadt, Kassel, and Essen) for two building density ranges for each of three building height ranges (see Graphs 16a,b,c and 17a,b,c). For purpose of comparison, these curves were then transferred to tabular form (see Table V). Comparison of these data does not show a consistent correlation of increasing burned-to-unburned distance with increasing building density or with increasing building height. For building density of 30.5 to 45.4 per cent, there is fairly good correlation of increasing exposure distance with increasing building height, whereas for 45.5 to 60.4 per cent building density there seems to be no correlation. For building height of 45 to 55 feet, there is good correlation of increasing distance with increasing building density, whereas for building heights of 35 to 45 feet and 55 to 65 feet there seems to be no correlation.

Similar curves and tabulations were made for the four Japanese cities of Hiroshima, Nagasaki, Kure, and Sakai for four building density ranges and two building height ranges (see Graphs 18; 19a,b; 20a,b; and 21; and Table VI). Comparison of these data does not show a consistent correlation of increasing burned-to-unburned distance with increasing building density or with increasing building height. For building density of 46 to 60 per cent, there is good correlation of increasing exposure distance with increasing building height, whereas for 31 to 45 per cent building density no correlation is indicated. For any given building height range, there is no correlation shown between exposure distance and building density. This lack of correlation may be due to the fact that the data do not represent a good distribution over the four cities studied. Examination of the data shows the following:

(1) the data for Graphs 18, 19b, and 20b were derived preponderantly from the atomic-attacked cities of Hiroshima and Nagasaki;

(2) the data for Graphs 19a and 20a were fairly evenly divided between the atomic-attacked cities of Hiroshima and Nagasaki and the incendiary-attacked cities of Kure and Sakai; and

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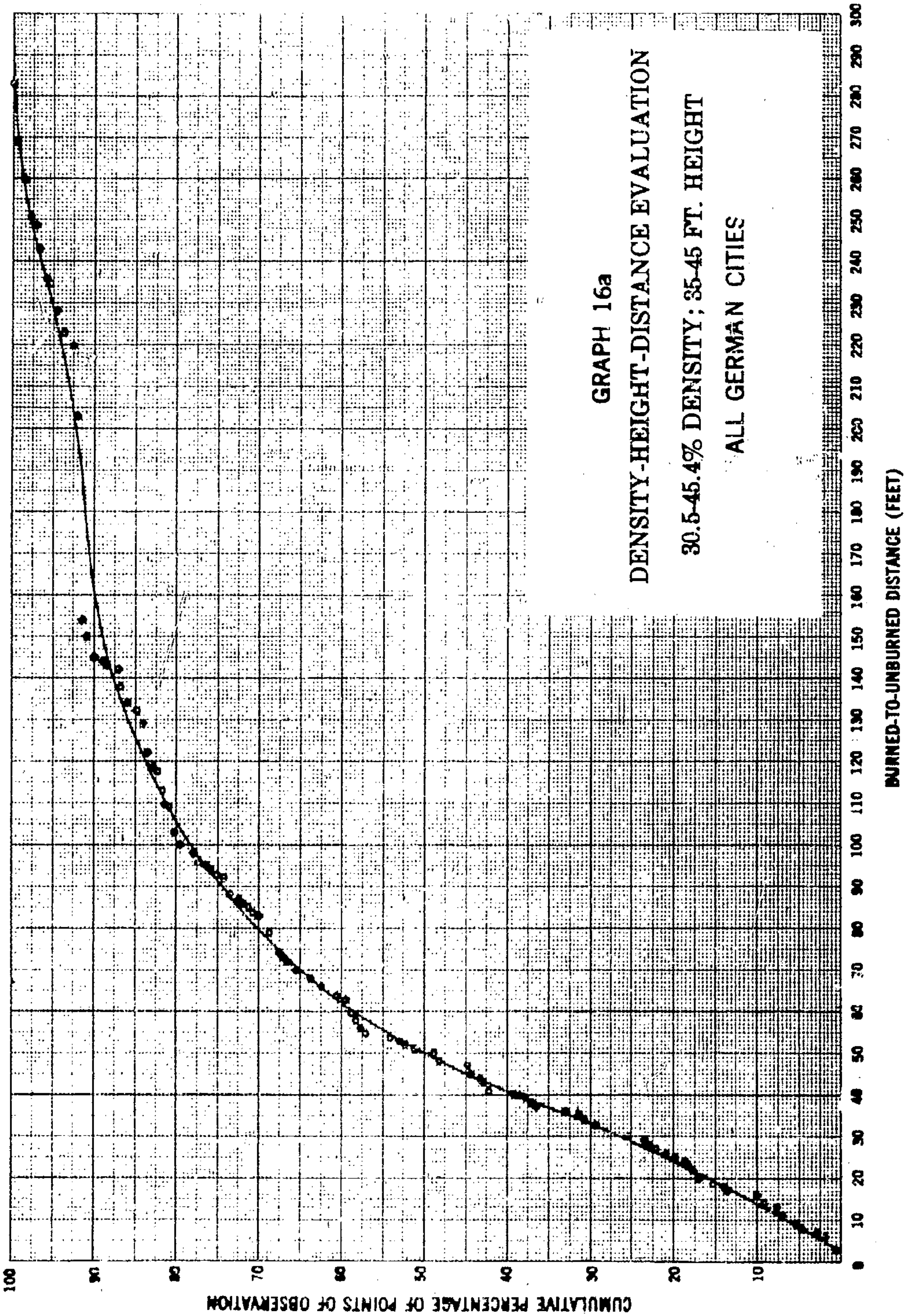
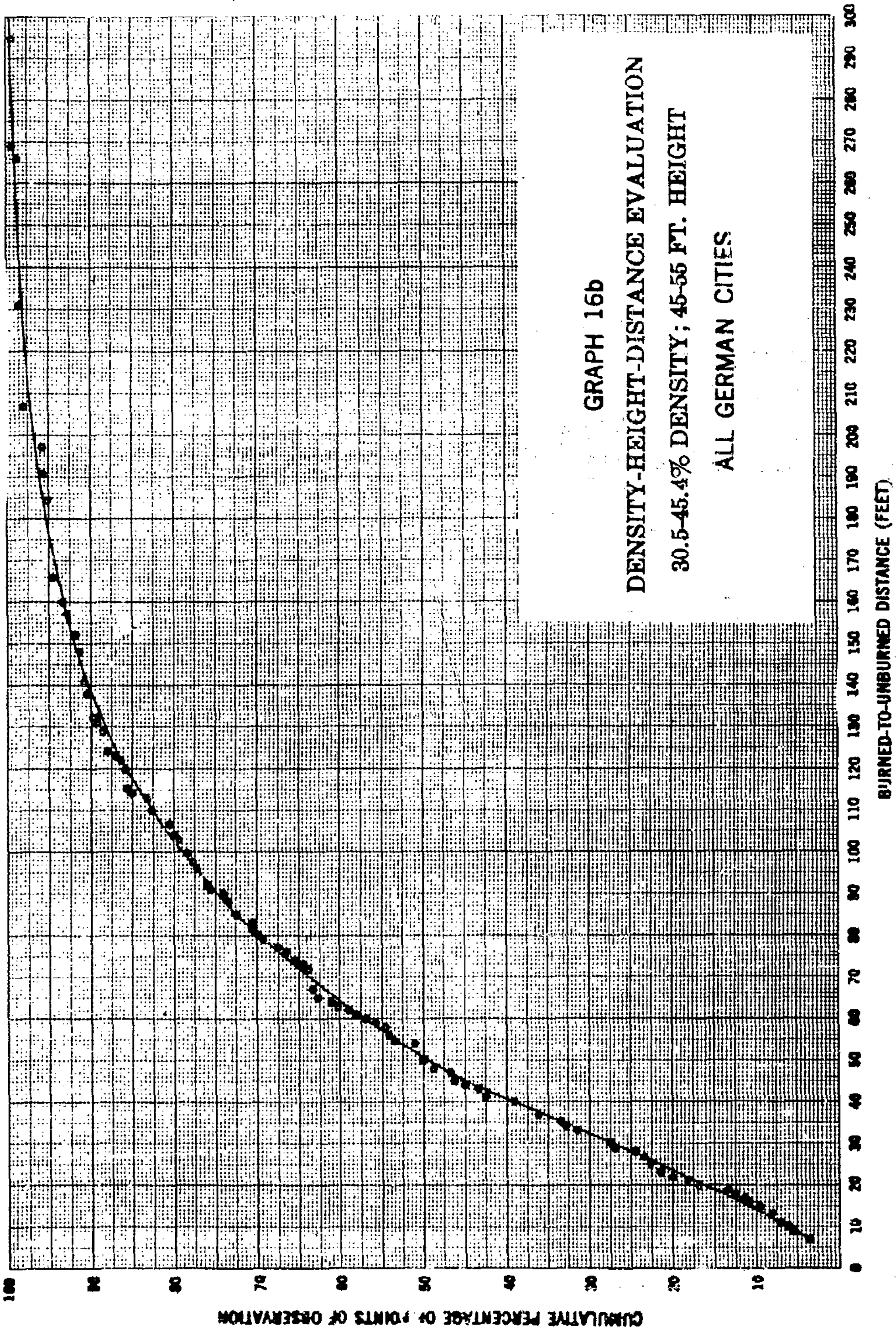
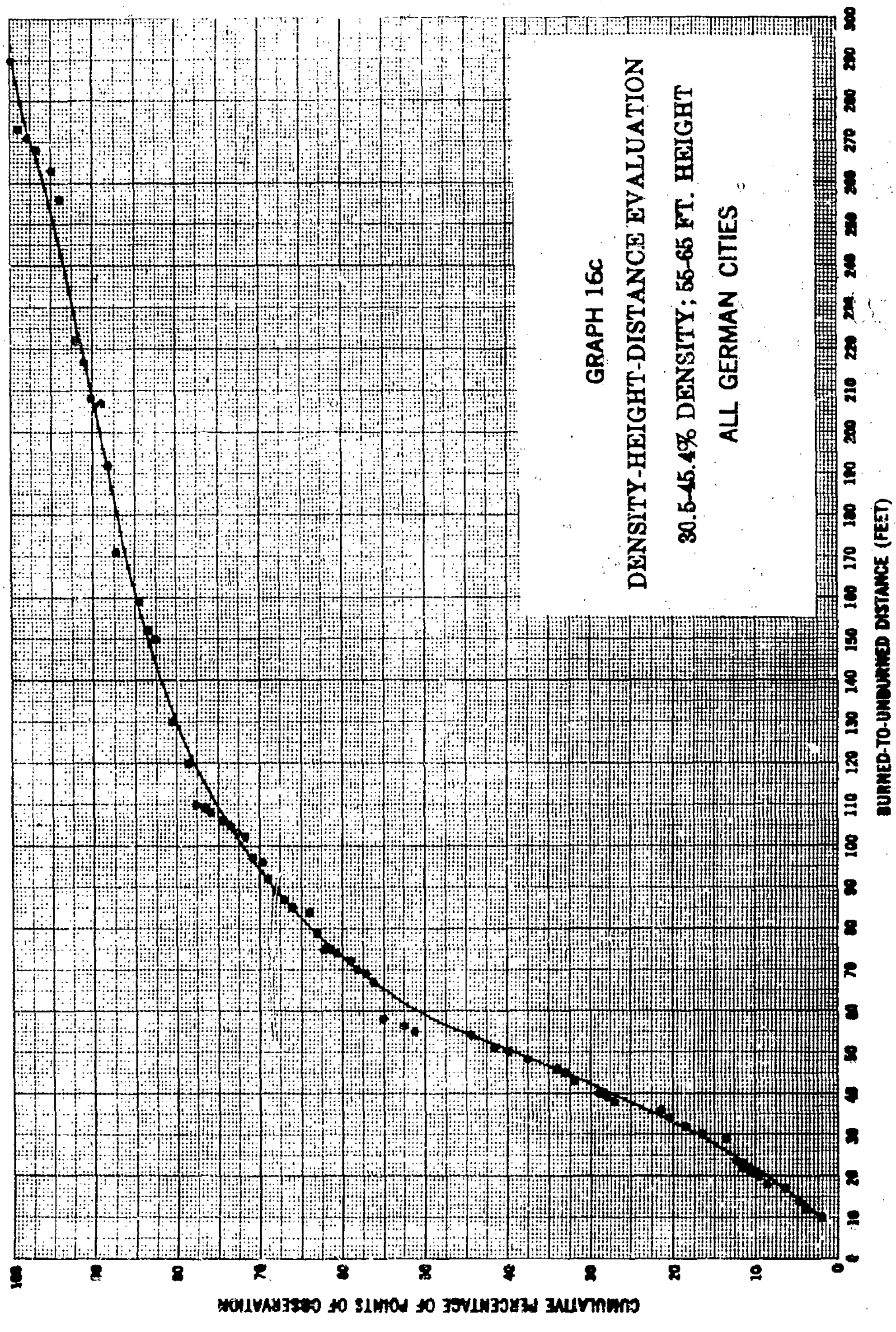
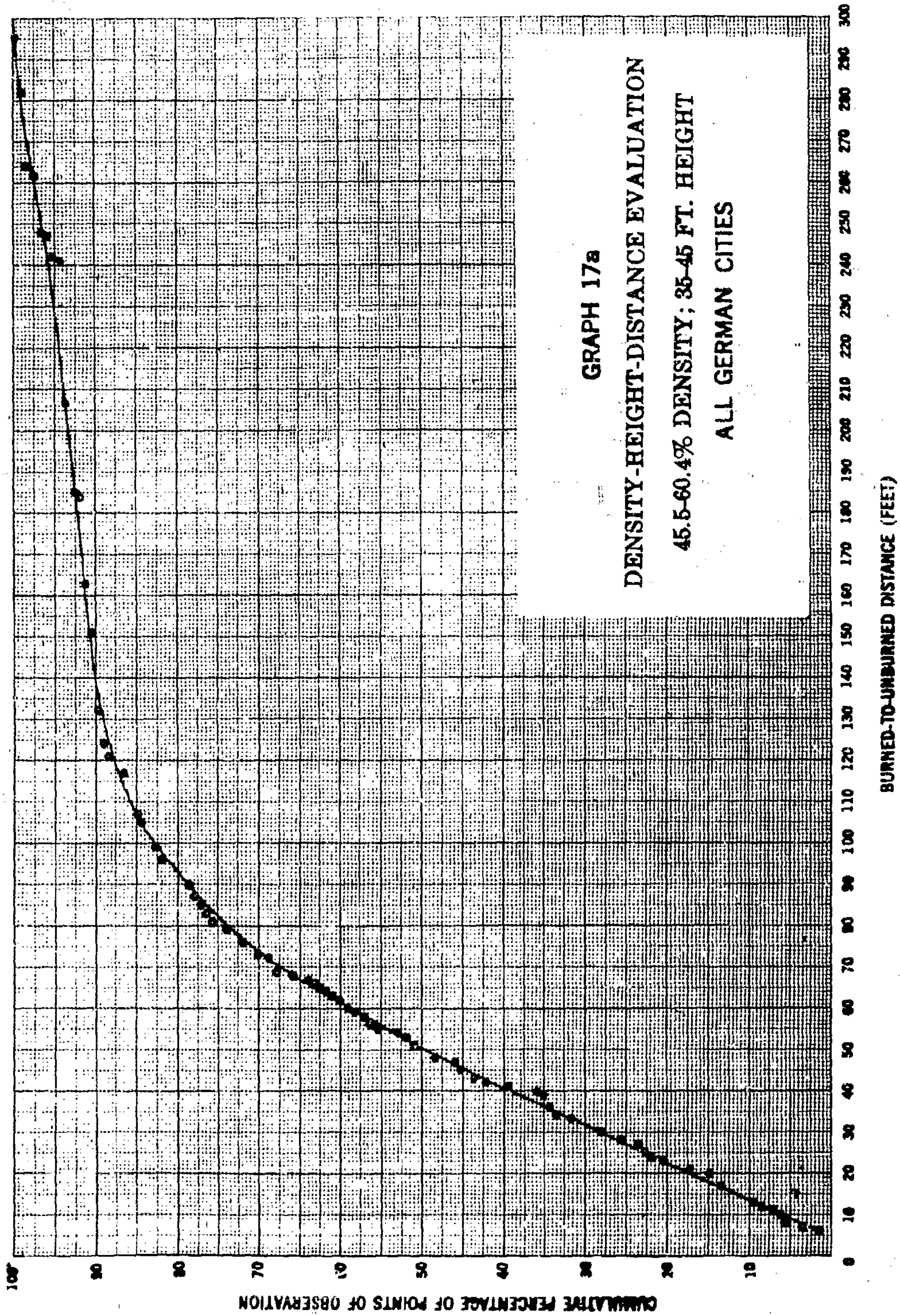
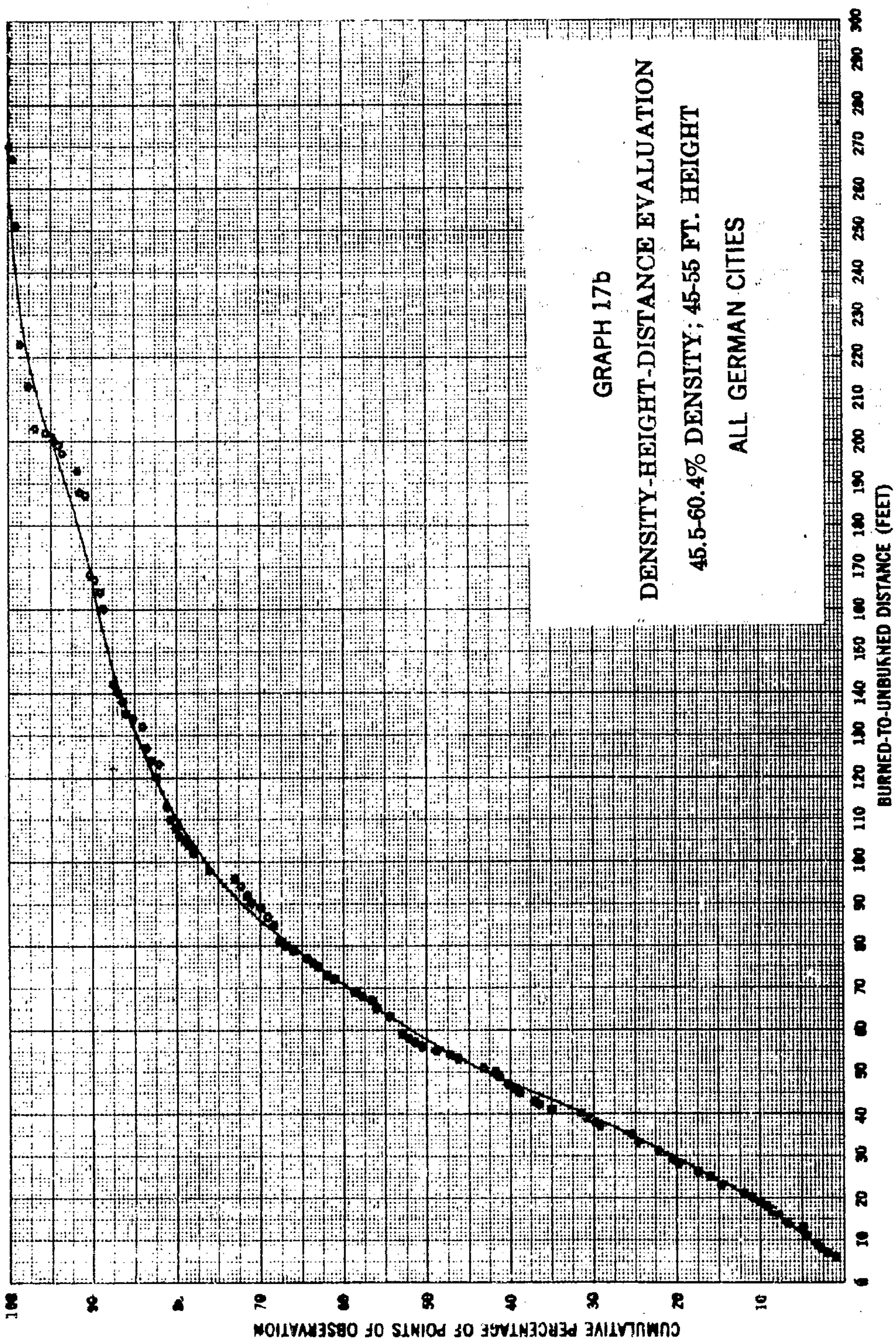
1/ These tables are included in the Working Papers of Test V.


GRAPH 16a
DENSITY-HEIGHT-DISTANCE EVALUATION
30.5-45.4% DENSITY; 35-45 FT. HEIGHT
ALL GERMAN CITIES
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 16b
DENSITY-HEIGHT-DISTANCE EVALUATION
30.5-45.4% DENSITY; 45-55 FT. HEIGHT
ALL GERMAN CITIES
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 16c
DENSITY-HEIGHT-DISTANCE EVALUATION
30.5-45.4% DENSITY; 55-65 FT. HEIGHT
ALL GERMAN CITIES
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 17a
DENSITY-HEIGHT-DISTANCE EVALUATION
45.5-60.4% DENSITY; 35-45 FT. HEIGHT
ALL GERMAN CITIES
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 17b
DENSITY-HEIGHT-DISTANCE EVALUATION
45.5-60.4% DENSITY; 45-55 FT. HEIGHT
ALL GERMAN CITIES
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION

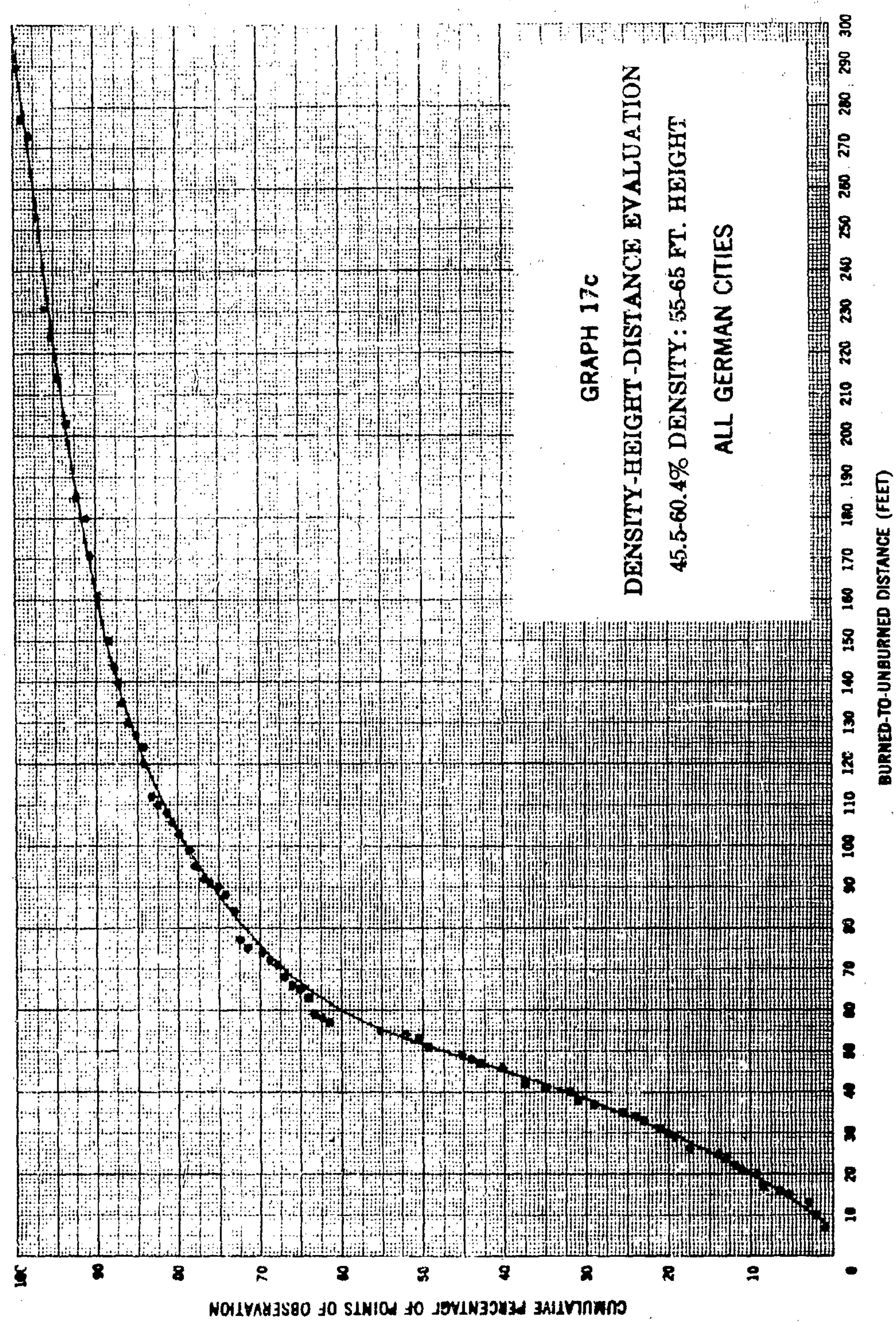
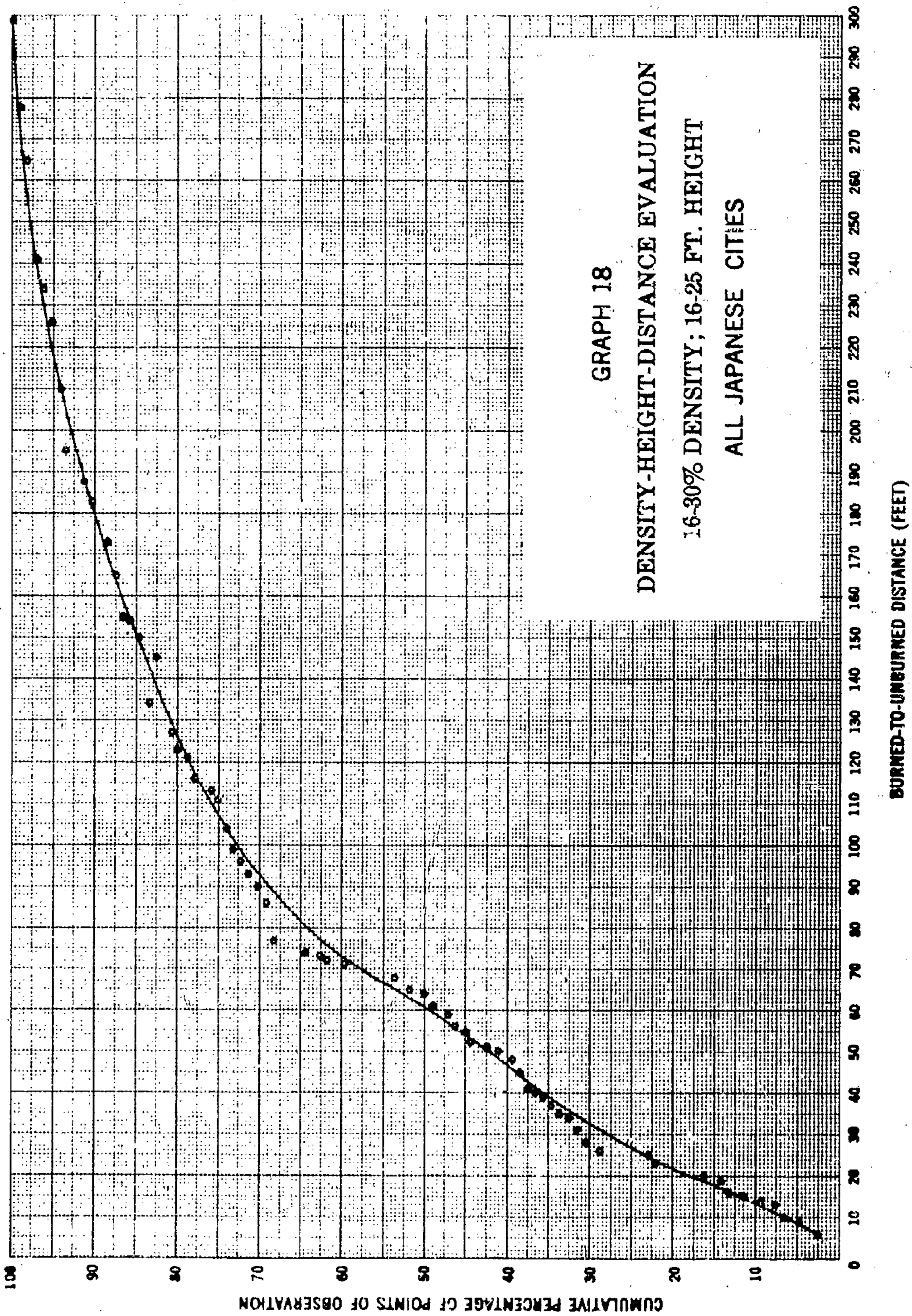
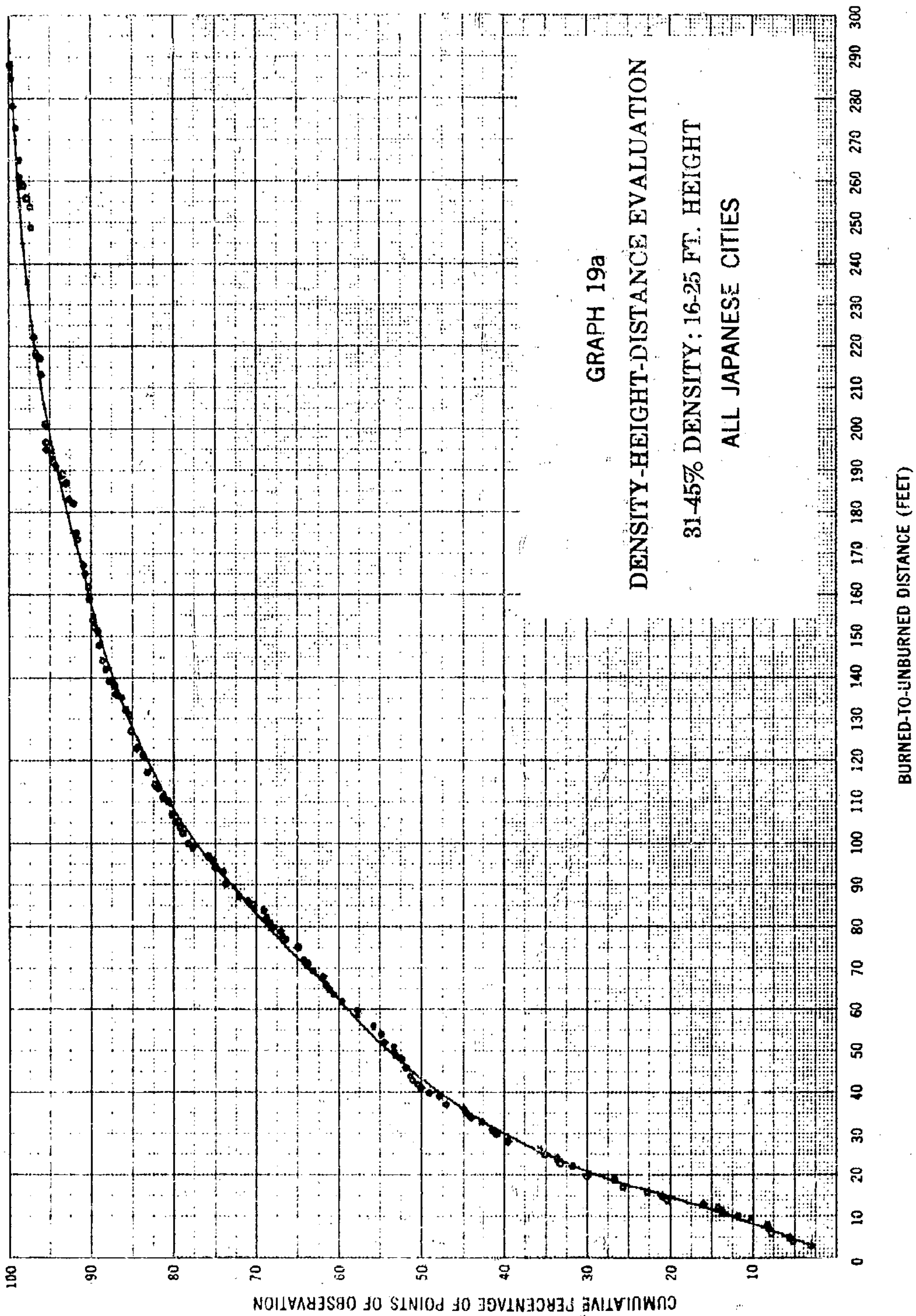

GRAPH 17c
DENSITY-HEIGHT-DISTANCE EVALUATION
45.5-60.4% DENSITY: 55-65 FT. HEIGHT
ALL GERMAN CITIES
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION

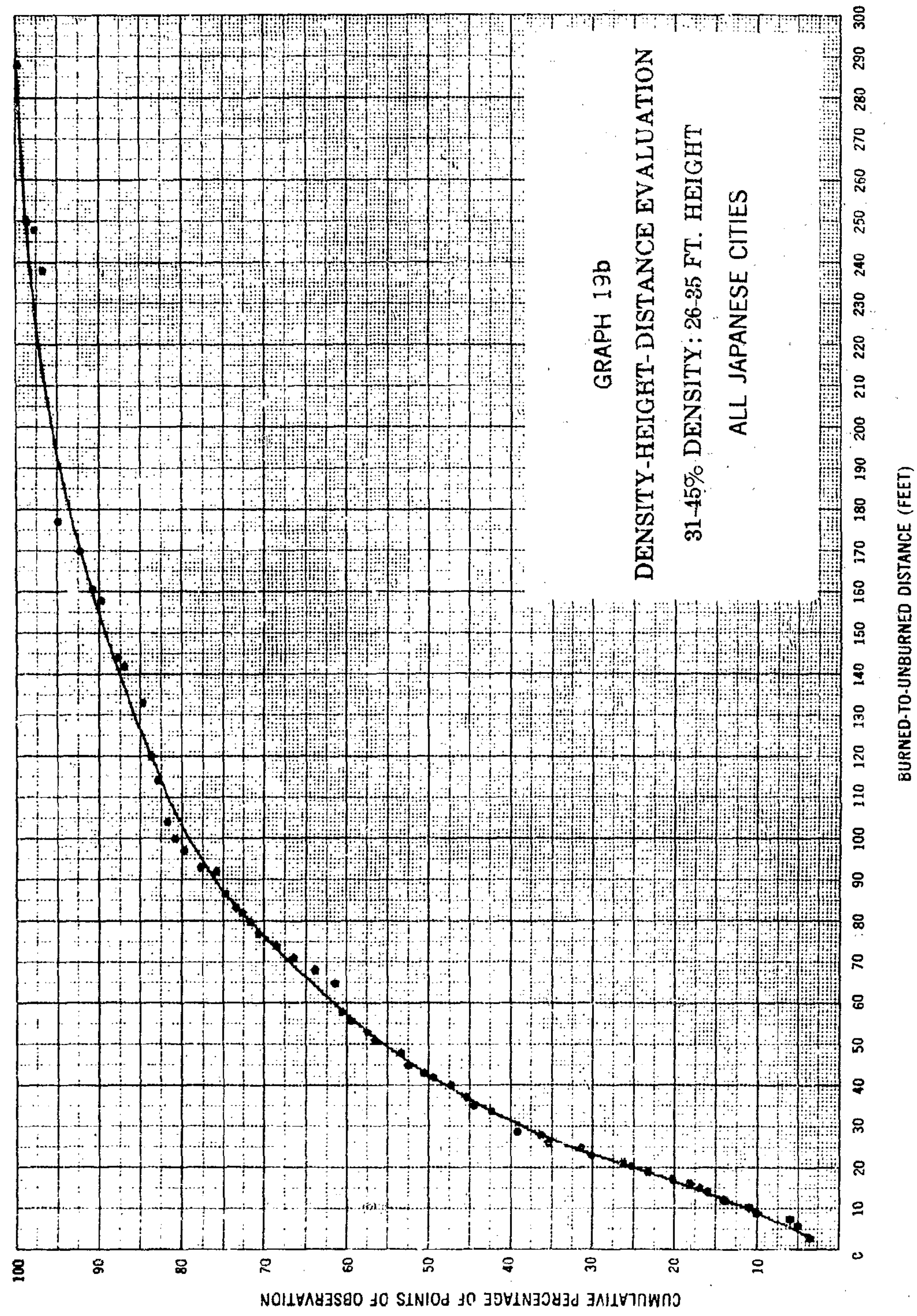
TABLE V

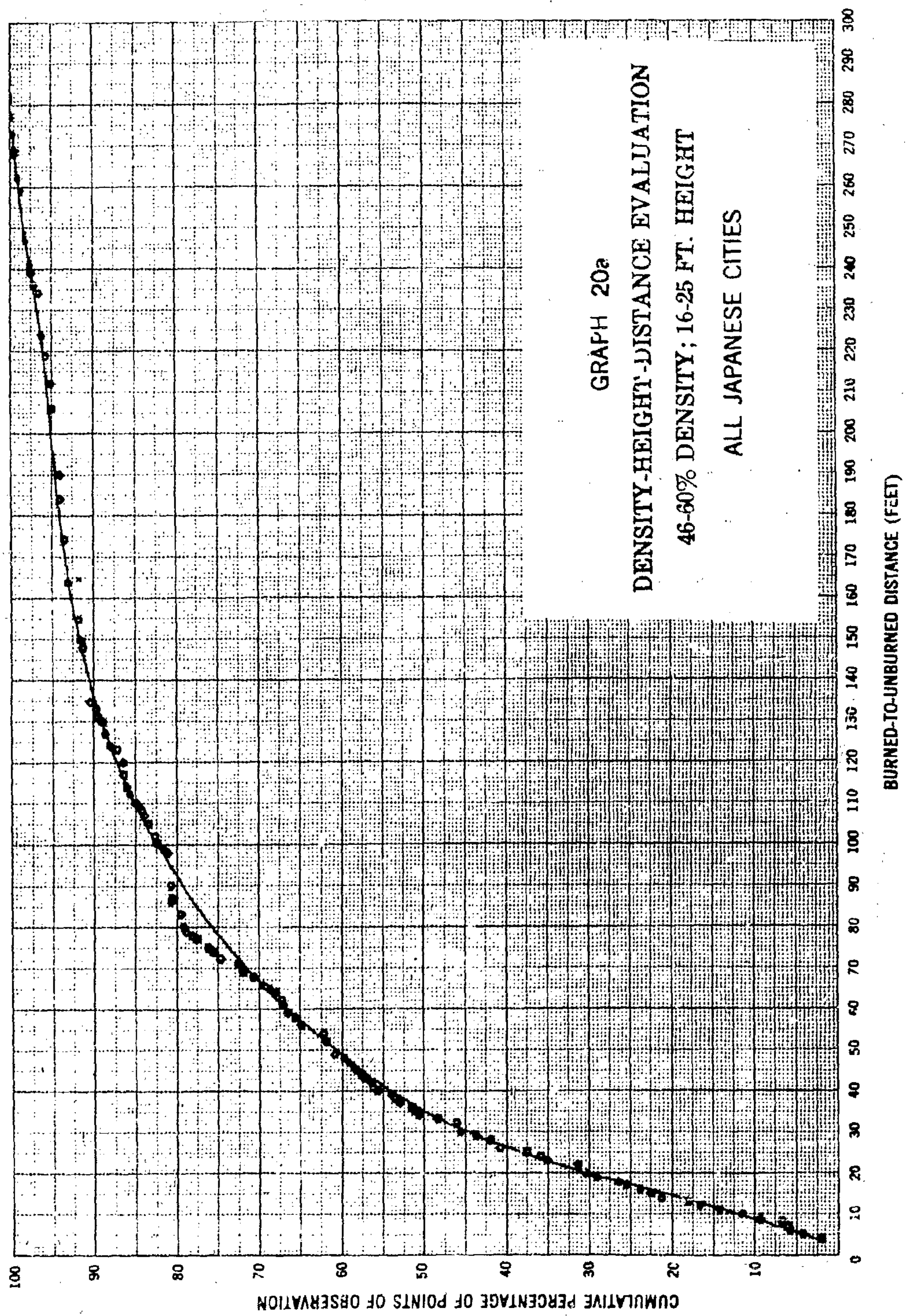
DENSITY-HEIGHT-DISTANCE EVALUATION
ALL GERMAN CITIES
(HAMBURG, BARMEN, ELBERFELD, ESSEN, KASSEL, DARMSTADT)

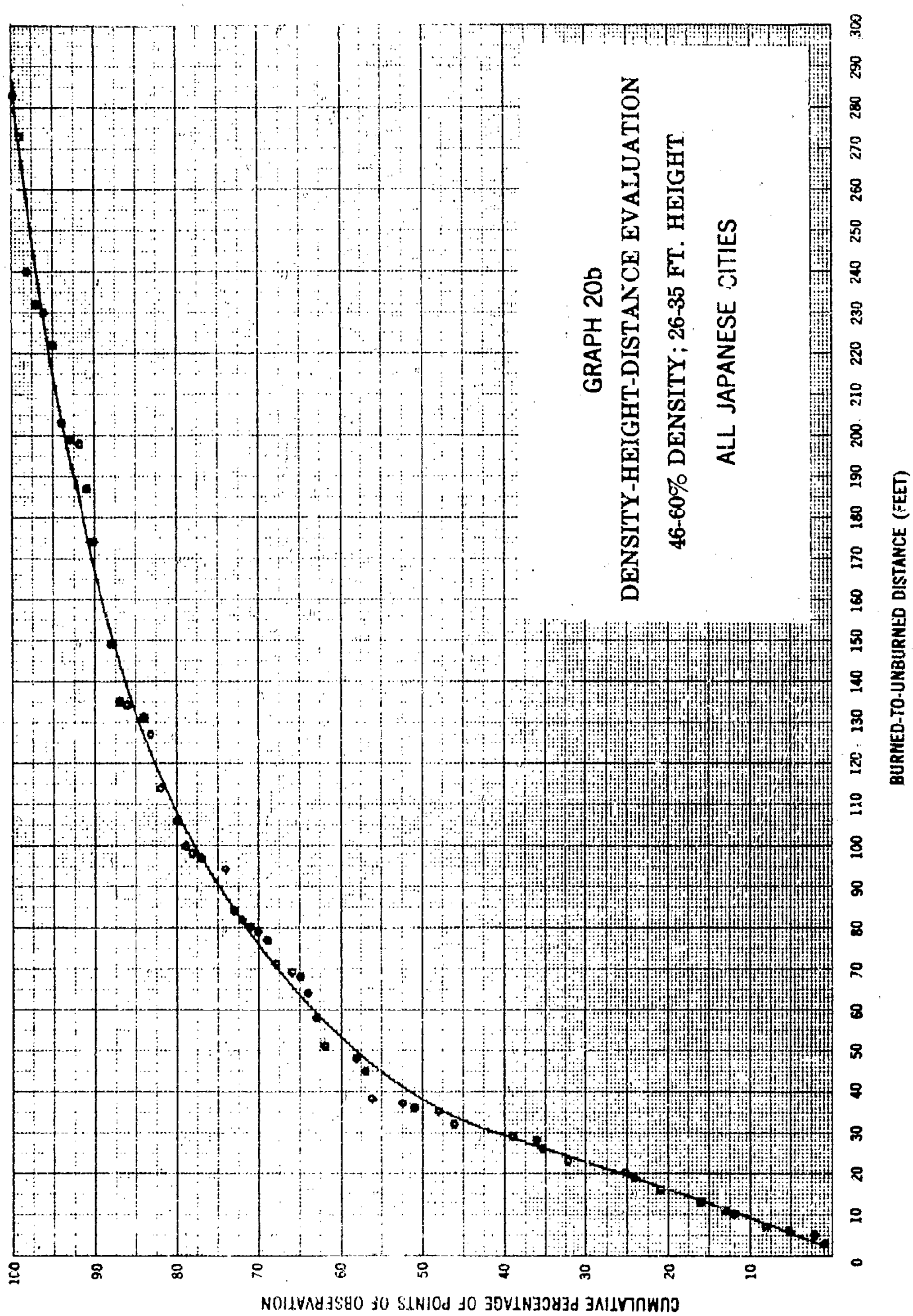
Burned-to Unburned Distance (in Feet)	Cumulative Percentage of Points of Observation at which Fire Stopped in Each Density and Height Range: 30.5 - 45.4% Density			45.5 - 60.4% Density		
	35'-45'	45' - 55'	55' - 65'	35' - 45'	45' - 55'	55' - 65'
10	6.0%	6.0%	2.0%	6.0%	4.0%	2.5%
20	16.0	16.0	8.5	17.0	11.0	10.0
30	26.5	27.0	17.0	28.0	20.5	20.0
40	39.0	39.5	27.5	39.5	31.0	32.5
50	50.0	49.5	39.0	44.5	42.5	47.5
60	58.5	57.0	51.0	59.0	52.0	60.0
70	65.0	64.0	58.0	67.5	59.5	67.0
80	70.0	70.0	63.5	73.5	66.0	72.0
90	74.5	74.5	68.5	78.5	72.0	76.0
100	78.5	79.0	72.0	83.0	76.5	79.0
110	81.0	82.5	75.0	85.5	80.0	81.5
120	83.5	85.5	78.0	87.5	82.5	84.0
130	86.0	88.5	80.0	89.0	85.0	86.0
140	87.5	90.0	82.0	90.0	86.5	87.5
150	89.0	92.0	83.5	90.5	88.0	88.5
300	100.0	100.0	100.0	100.0	100.0	100.0
Number of Points of Observation:	170	186	103	128	182	109
Graph Number	16a	16b	16c	17a	17b	17c


GRAPH 18
DENSITY-HEIGHT-DISTANCE EVALUATION
16-30% DENSITY; 16-25 FT. HEIGHT
ALL JAPANESE CITIES
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300


GRAPH 19a
DENSITY-HEIGHT-DISTANCE EVALUATION
31-45% DENSITY; 16-25 FT. HEIGHT
ALL JAPANESE CITIES
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 13b
DENSITY-HEIGHT-DISTANCE EVALUATION
31-45% DENSITY; 26-35 FT. HEIGHT
ALL JAPANESE CITIES
BURNED-TO-UNBURNED DISTANCE (FEET)
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION
100 90 80 70 60 50 40 30 20 10


GRAPH 20a
DENSITY-HEIGHT-DISTANCE EVALUATION
46-60% DENSITY; 16-25 FT. HEIGHT
ALL JAPANESE CITIES
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 20b
DENSITY-HEIGHT-DISTANCE EVALUATION
46-60% DENSITY; 26-35 FT. HEIGHT
ALL JAPANESE CITIES
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300
100 90 80 70 60 50 40 30 20 10

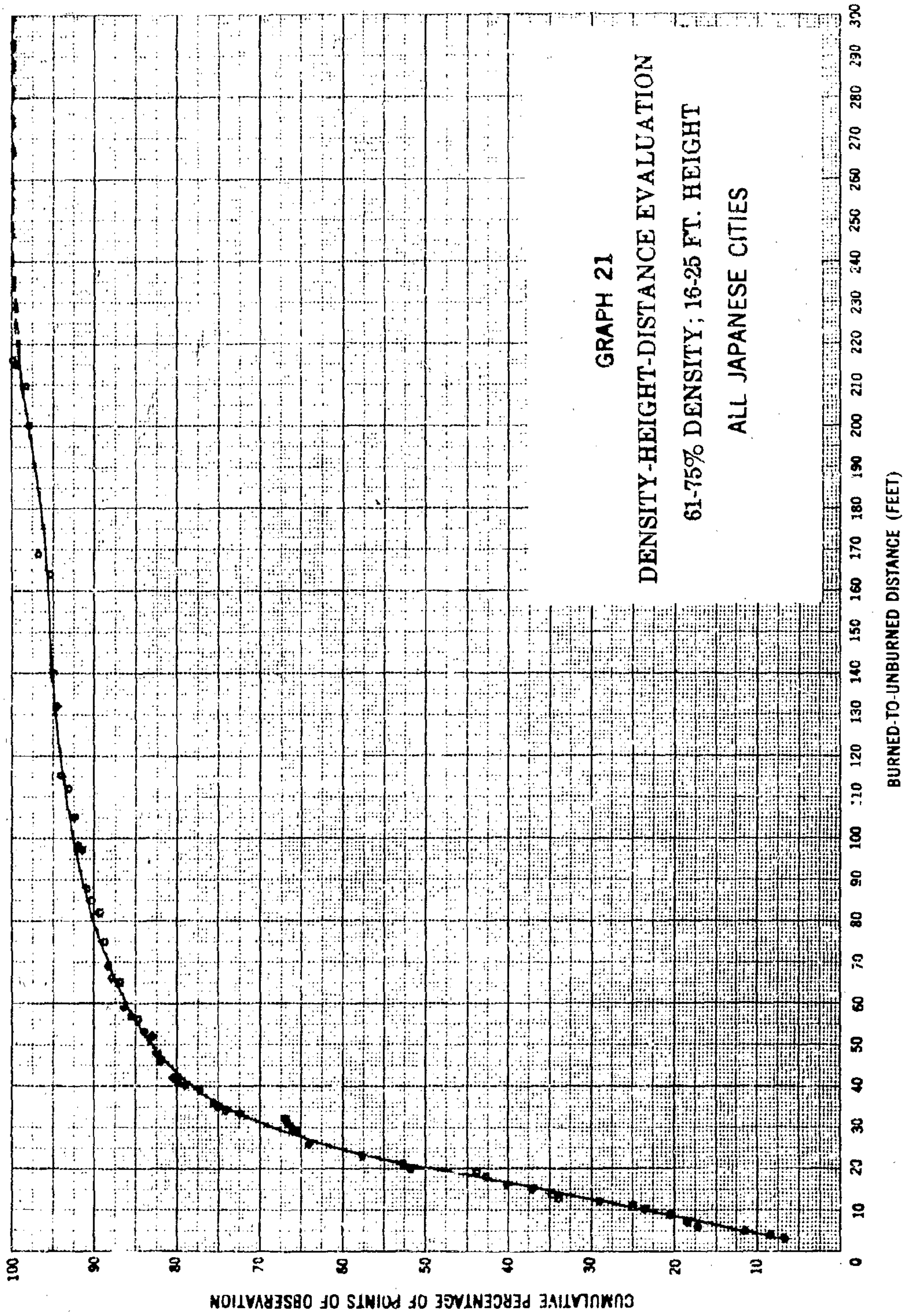

GRAPH 21
DENSITY-HEIGHT-DISTANCE EVALUATION
61-75% DENSITY; 16-25 FT. HEIGHT
ALL JAPANESE CITIES
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION

TABLE VI

DENSITY-HEIGHT-DISTANCE EVALUATION
ALL JAPANESE CITIES
(NAGASAKI, HIROSHIMA, KURE, AND SAKAI)

Burned-to-Unburned Distance (in Feet)	Cumulative Percentage of Points of Observation at which Fire Stopped in Each Density and Height Range					
	16-30% Density	31-45% Density		46-60% Density		61-75% Density
	16'-25'	16'-25'	26'-35'	16'-25'	26'-35'	16'-25'
10	6.0%	2.5%	11.5%	12.0%	11.0%	23.0%
20	18.0	29.0	25.0	30.5	26.0	49.5
30	28.0	40.0	39.0	45.0	41.0	68.5
40	36.0	48.0	48.0	54.0	51.5	78.0
50	42.0	54.0	55.0	61.0	58.0	83.0
60	49.5	59.0	61.5	67.0	63.5	86.0
70	57.5	64.0	67.0	71.5	68.0	88.0
80	64.0	68.5	71.5	75.5	71.5	90.0
90	69.0	73.0	76.0	79.0	75.0	91.5
100	72.5	77.0	79.0	82.5	78.0	92.5
110	76.0	80.5	81.5	85.0	80.5	93.5
120	78.5	83.0	83.5	87.0	82.5	94.0
130	81.0	85.5	85.5	89.0	84.5	94.5
140	83.0	87.5	87.5	90.5	86.5	95.0
150	85.0	89.0	89.5	91.5	88.0	95.5
300	100.0	100.0	100.0	100.0	100.0	100.0
Number of Points of Observation:	88	335	99	311	100	175
Graph Number:	18	19a	19b	20a	20b	21

(3) the data for Graph 21 were derived preponderantly from Kure. The percentage of the total points of observation contributed by the individual Japanese cities to each graph is shown in Table VII. Comparison of Graph 18 (91 per cent of points from Hiroshima and Nagasaki) with Graph 21 (98 per cent of points from Kure and Sakai) shows that greater distances were required to stop fire spread at the final perimeter of the mass fire areas in the atomic-attacked cities than in the incendiary-attacked cities.

TABLE VII

Distribution of Points of Observation in Density-Height-Distance Evaluation

Japanese Cities

City	Graph 18	Graph 19a	Graph 19b	Graph 20a	Graph 20b	Graph 21
Hiroshima	75%	49%	61%	44%	14%	2%
Nagasaki	16	5	36	13	75	1
(Atomic)	(91)	(54)	(97)	(57)	(89)	(2)
Kure	0	11	1	14	4	88
Sakai	9	35	2	29	7	10
(Non-Atomic)	(9)	(46)	(3)	(43)	(11)	(98)

PART IV

SUMMARY DISCUSSION

Wind, temperature, rain, humidity, terrain, building construction and contents loading, building areas and heights, building density, building contiguity, and firefighting activity are the principal variables which affect fire spread. The objective of this research was to determine which of these variables exercised significant effects on building-to-building spread of fire, for the purpose of developing the capability of predicting the vulnerability of urban areas to fire spread. Unfortunately, lack of definitive information about meteorological conditions preceding and during the wartime conflagrations studied made it infeasible to evaluate the effects of wind, temperature, rain, and humidity on fire spread. Information about terrain and firefighting also was too generalized or too meager to permit evaluation of their effects. Therefore, quantitative evaluations of important fire spread parameters had to be limited to those analyses which could be made with pre-attack and post-attack photography.

In the great conflagration of Chicago, the fire, fanned by wind, melted pig iron 200 feet from the burning area. 1/ Other cases where wind took complete control of fire direction and increased the intensity of the heat are the great fires of Baltimore, San Francisco, and Tokyo. In such cases, distance between buildings was of little account. Wind probably had little, if any, effect on the fires in some of the cities analyzed in this study; in others, either directly or by carrying flying firebrands, wind may have spread the fire across distances which would have been safe under normal conditions; and in still other cities, buildings which normally would have been in danger may have been saved because wind blew the flames and heat away from them. It was not possible to assess the relative effects of wind either as a retarding or increasing influence on the spread of fire in the cities studied. It would appear that an average of the effects of wind in the German and Japanese cities would be represented if, for each type of city, all the points-of-observation data for burned-to-unburned distances at the fire perimeters were consolidated. Likewise, an average of the effects of other meteorological factors, and of topographical factors, on fire spread would probably be reflected by such a consolidation of the data collected.

Deciduous trees in leaf undoubtedly played some part in retarding the spread of fire between buildings. Instances where the fire stopped along a line of trees were observed on the photography. Also, there were several instances where buildings remained unburned within the burned-over area, and it was noted that many of these buildings were shielded by trees. It is possible that the effect of trees may be the cause of some of the variance in the cumulative curves for individual cities studied, but the degree of effect would probably be small when taken as an average of the total number of points of observation for either the Japanese or the German cities.

Building construction and contents loading, or the amount of combustibles in a city, have a very important effect on the spread of fire.

1/ James W. Sheehan and George P. Upton, The Great Conflagration Chicago, Union Publishing Co., Chicago, pp. 121-123.

Research has shown that light frame Japanese buildings burned rapidly and completely, leaving nothing to retain sufficient heat to ignite nearby buildings by radiation; also, especially near the fire perimeter, the light construction and low height of these buildings made it possible to use firefighting effectively to halt fires at very short distances. On the other hand, in German cities the buildings were larger and of heavier construction; consequently, the fires in individual buildings were bigger and burned longer, and the masonry walls retained heat and acted as radiating bodies over long periods of time, making ignition of exposed buildings more likely. All other factors being equal, it could be expected that, on the average, fire would spread across a given distance more frequently in a German city than in a Japanese city.

Reports of previous research have indicated that one of the most important factors affecting fire spread in urban areas is building density. There is no doubt about the importance of this factor; however, the density-distance evaluation in Test III failed to establish any consistent relationship between building density and the distances which stopped fire in either German or Japanese cities.

The construction, plan area, and height of buildings, and the type and quantity of building contents are also acknowledged as important factors affecting fire spread in urban areas. However, in wartime analyses of the fire vulnerability of urban areas, these factors have been given consideration only in a general, qualitative manner. In this study, building volume was selected as a broad, quantitative measure of the fire load (total BTU value of combustible building construction materials and contents) which would roughly reflect the over-all characteristics of building and contents having effect on fire spread. Unfortunately, the volume-distance evaluation in Test IV failed to establish any consistent correlation between building volume and the distances which stopped fire in either German or Japanese cities. Similarly, the density-height-distance evaluation in Test V, in which density-height reflected building volume or fire load in a somewhat more refined way, failed to establish any consistent correlation between various density-height combinations and the distances which stopped fire.

Since it was not possible to establish consistent correlations of density, volume, and density-height combinations with distances which stopped fire, it was decided to develop for the German cities, and for the Japanese cities, consolidated curves for cumulative points of observation versus corresponding burned-to-unburned distances, without regard to variations of building density, volume, and height at the fire perimeters. Unconsolidated curves of this type were developed in Test II for the German cities of Elberfeld, Barmen, and Darmstadt, and for the Japanese city of Kure. The curves for the three German cities showed fairly good correlation, and their correlation with the curve for the Japanese city was reasonable in view of the relatively light construction of the predominant type of Japanese building. Building construction and pattern in the German cities studied were fairly uniform, and the Japanese building construction and pattern were even more uniform. Therefore, there was good reason to expect that cumulative curves developed by consolidating all the burned-to-unburned distance data for the German cities and for the Japanese cities would be fairly representative of the average effects of the various structural factors in each of the two types of city. It was also anticipated that these consolidated curves would reflect the average effects of the meteorological

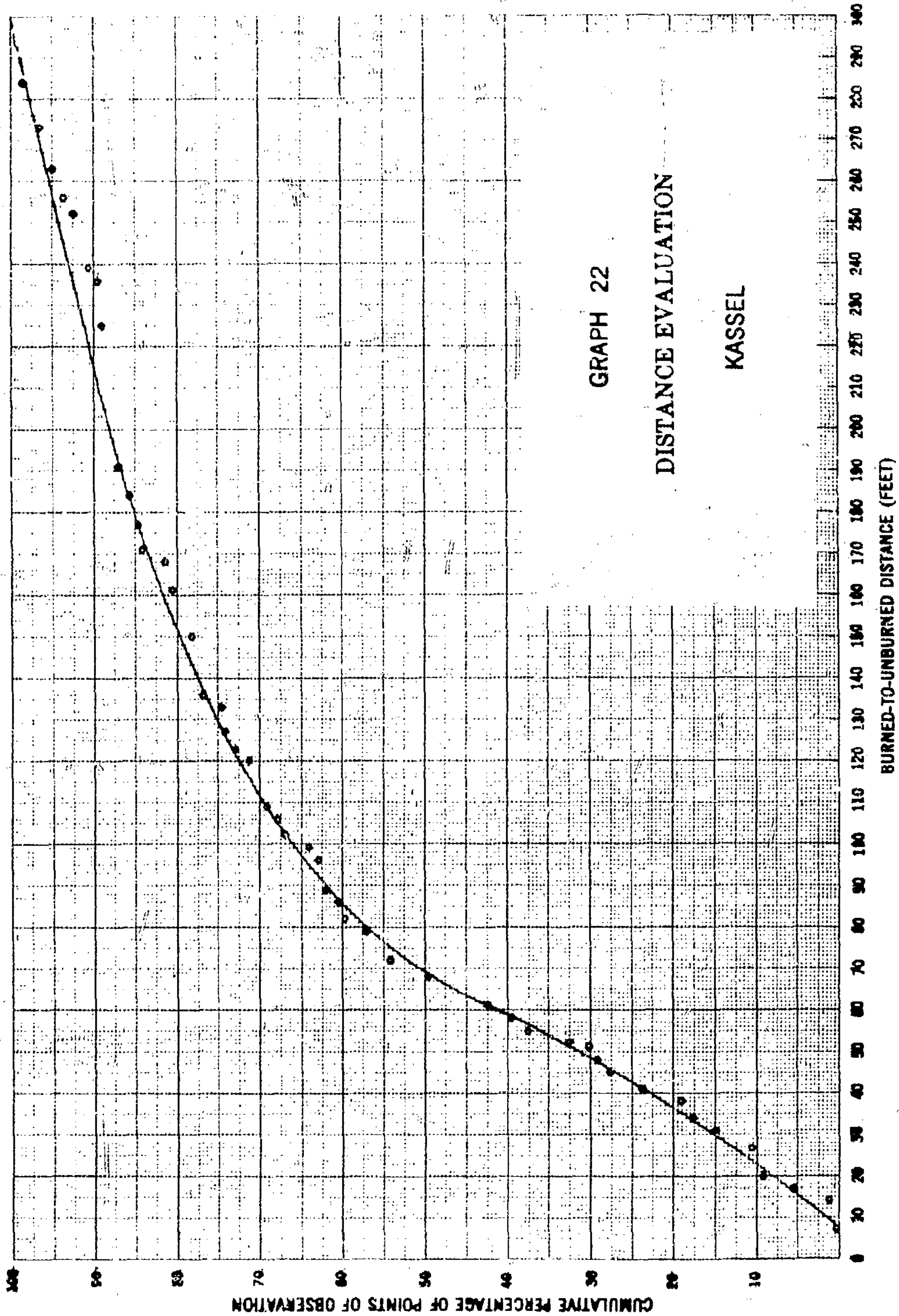
and physical variables, such as wind, temperature, rain, humidity, and topography, in the two types of city.

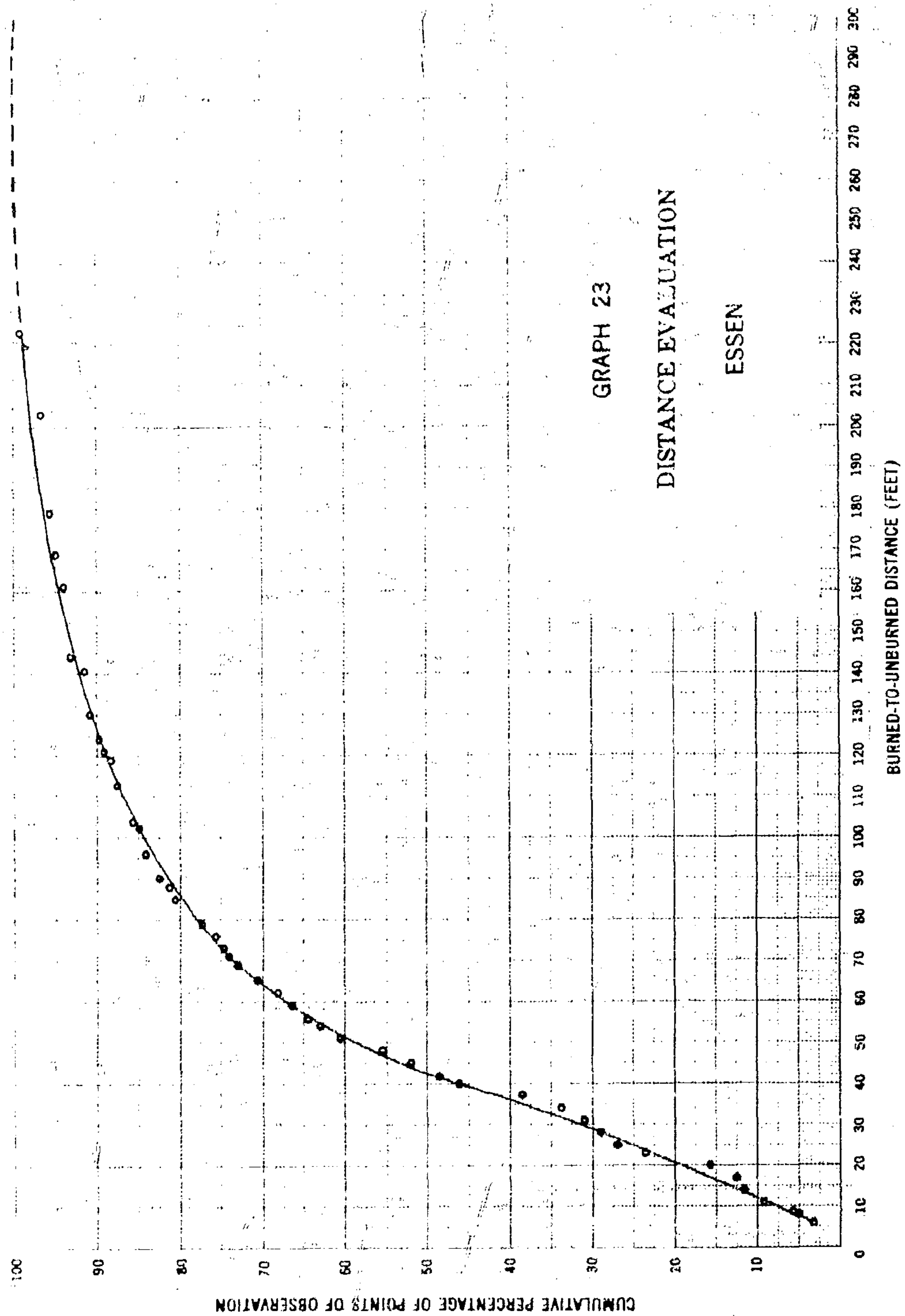
Curves for cumulative points of observation versus corresponding burned-to-unburned distances were developed for Kassel, Essen, Hamburg, Hiroshima, Nagasaki, and Sakai (see Graphs 22, 23, 24, 26, 27, and 29) similar to those previously developed in Test II for Elberfeld, Barmen, Darmstadt and Kure (see Graphs 5, 6, 7, and 8). The data was then used to develop consolidated curves for the six German cities (see Graph 25), the two atomic-attacked Japanese cities (see Graph 28), the two incendiary-attacked Japanese cities (see Graph 30), and all four Japanese cities (see Graph 31). For purpose of comparison, these curves were then transferred to tabular form (see Tables VIII and IX).

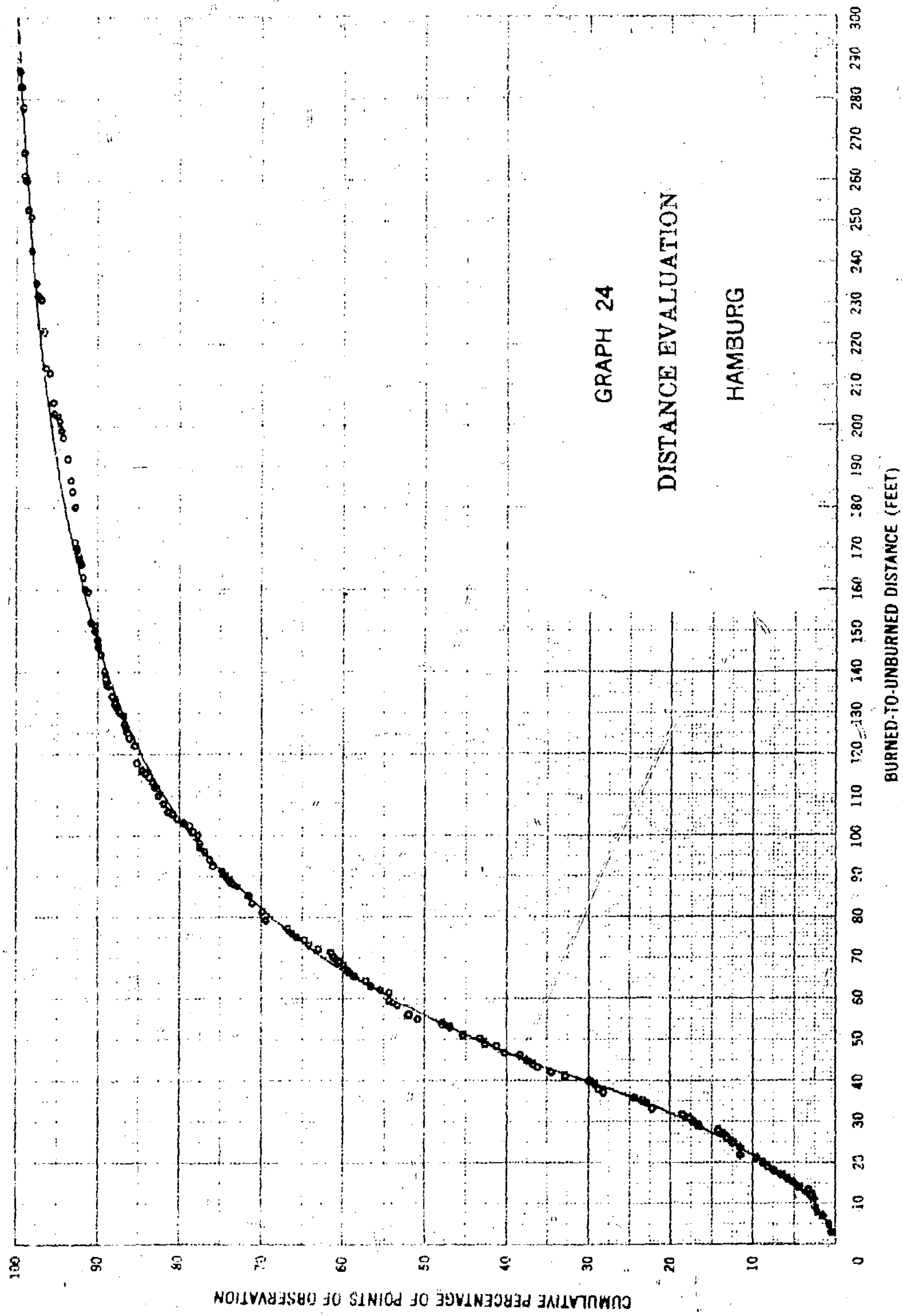
Zero distance was recorded for all points of observation where fire walls, party walls, firefighting, etc., stopped fire spread, but these zero measurements were not used in constructing the cumulative curves because interest was focused primarily on spread of fire across open space. The number and percentage of zero-distance observations in each city are shown in Table X; these are excluded from Tables VIII and IX. It is evident that the effects of fire walls and party walls (mainly in German cities) and probably firefighting played a part in halting spread of fire at the final fire perimeter. Within the areas containing great numbers of initial fires, whether ignited by thousands of incendiary bombs or by a single atomic bomb, party and fire walls were undoubtedly outflanked and rendered ineffective. In the outer areas of the German cities, where most if not all of the damage was due to building-to-building spread of fire, it was seen in areas of row or semidetached houses that fire stopped after destroying only part of the building. In many of these cases it was possible to confirm that party or fire walls had been effective in halting fire spread. The over-all percentage of zero-distance measurements in Japanese cities is comparatively small (9.6 per cent) because few fire or party walls exist in the Japanese-type construction. In the German cities, on the other hand, 26.8 per cent of the total observations were at zero distance. This illustrates the effectiveness of party and fire walls in the German cities, in halting the spread of fire within buildings and within city blocks. It is quite certain that practically all of the cases of zero distance in Japanese cities were the result of determined firefighting.

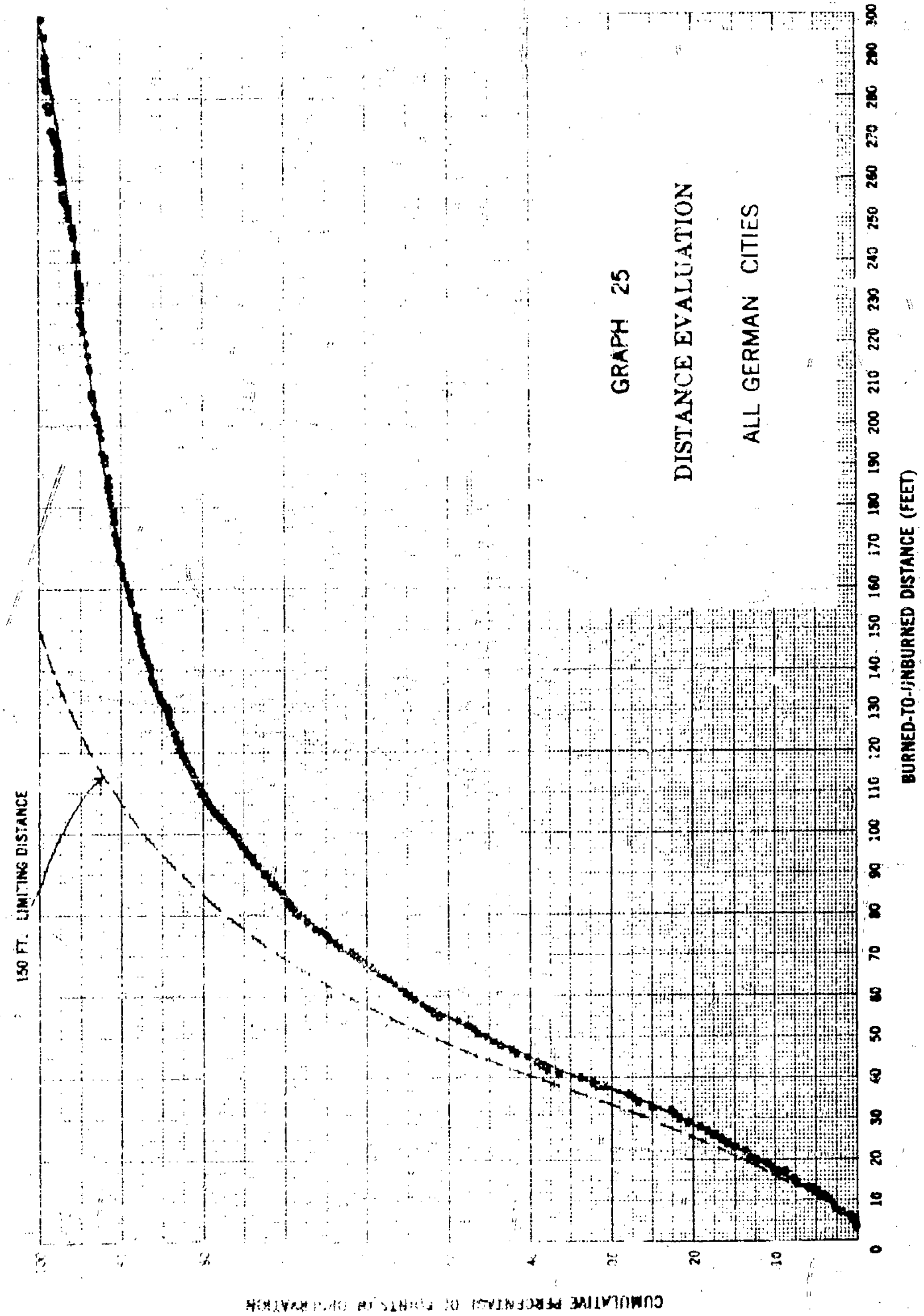
The zero-distance points of observation were not used in developing any of the cumulative curves; if these were used they would force the curves to the left. The resultant curves, when compared with the ones with zero-distance observations excluded, would then indicate that a given distance has a greater chance of stopping spread of fire. It is felt that the cumulative curves with zero-distance observations excluded will generally prove more useful for practical applications because analyses of urban area vulnerability to fire spread is more likely to be on a block-to-block (or larger subdivision) basis, in which case zero distances would not be a factor. However, if one desires, the number of zero-distance observations can be introduced, the percentages in Tables VIII and IX recomputed on the basis of the increased number of observations, and the cumulative curves replotted.

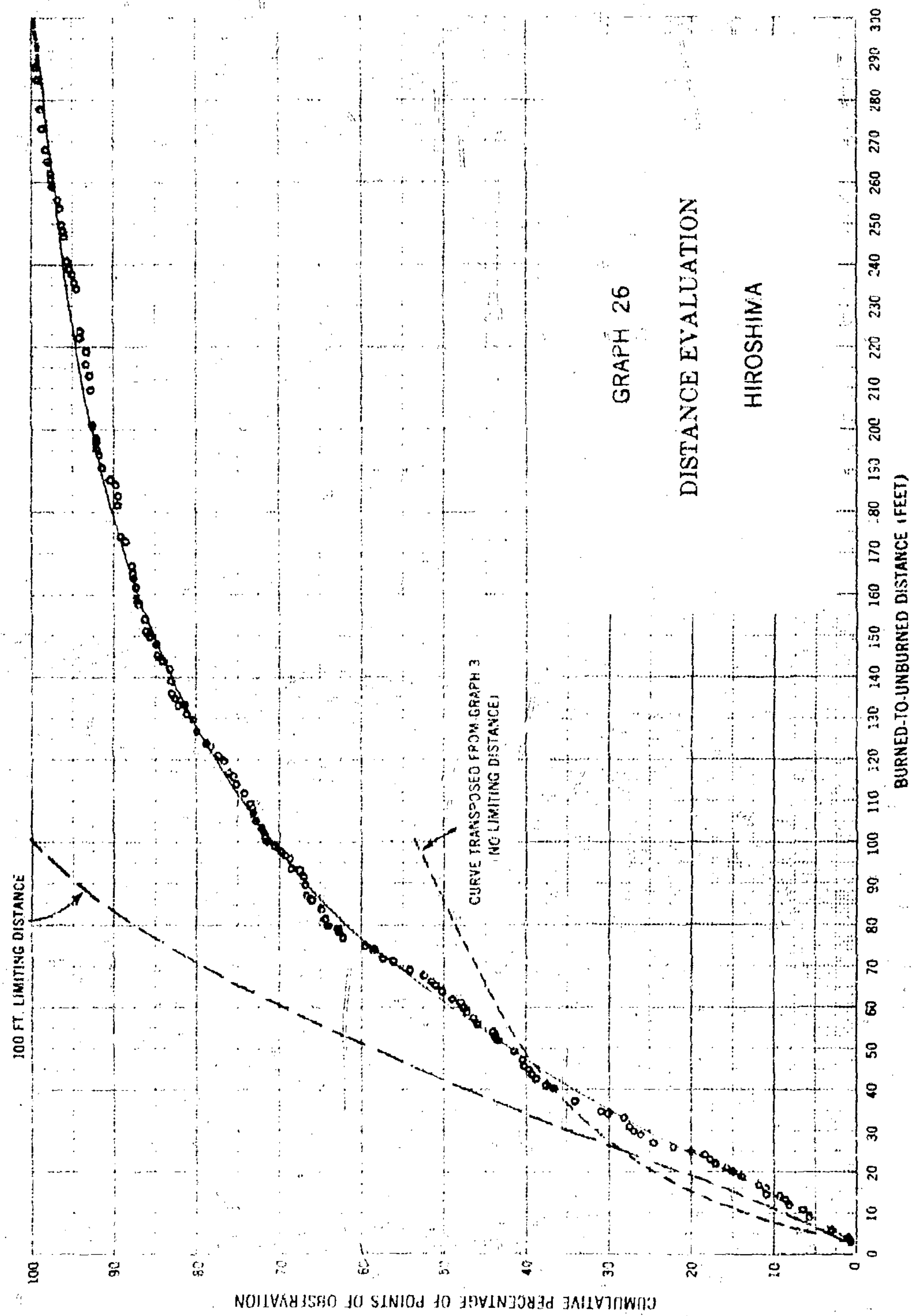
It will be noted that the curves and tabulations for Kure and Sakai give indication that fire apparently was stopped by shorter distances in Kure

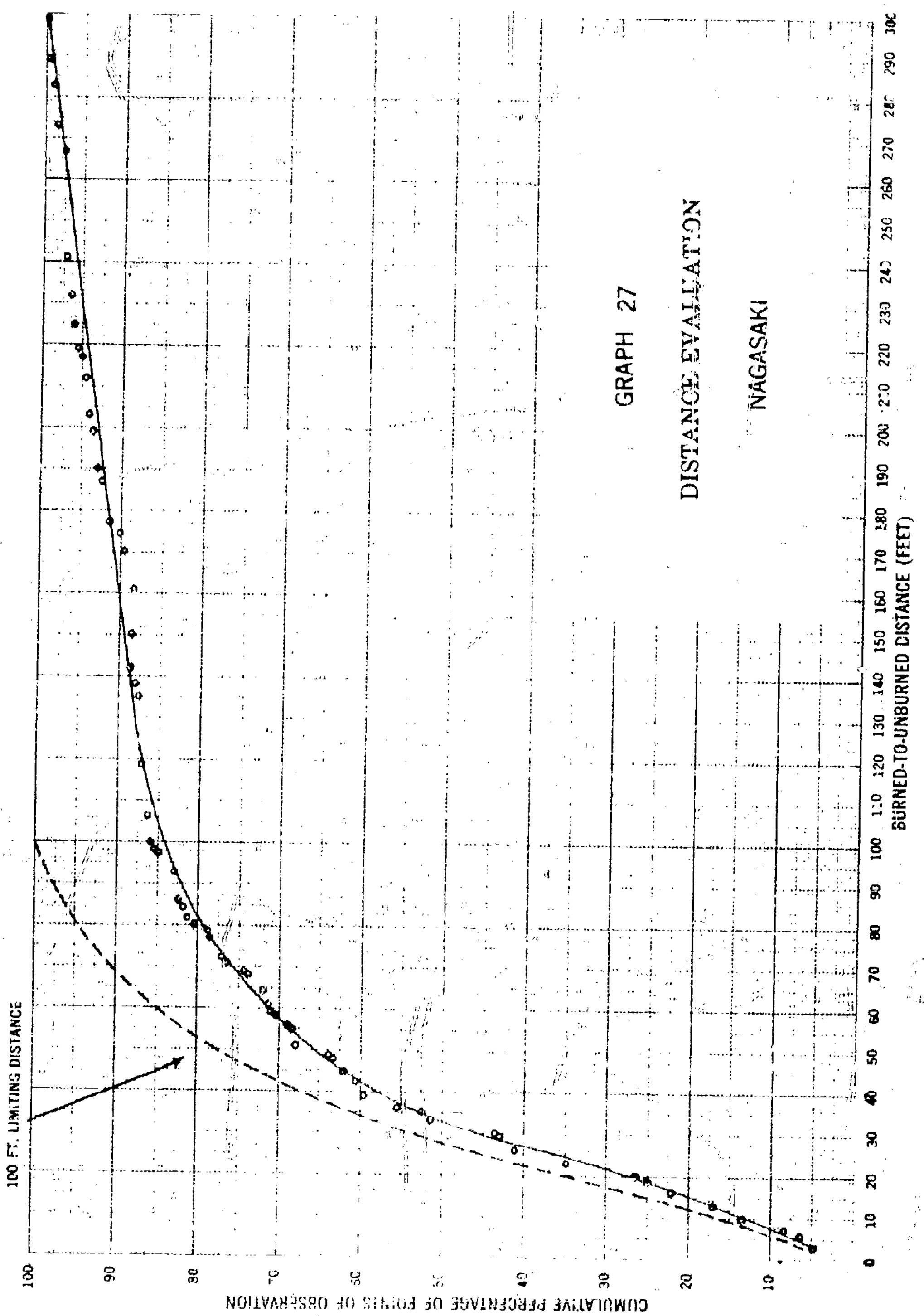

GRAPH 22
DISTANCE EVALUATION
KASSEL
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION

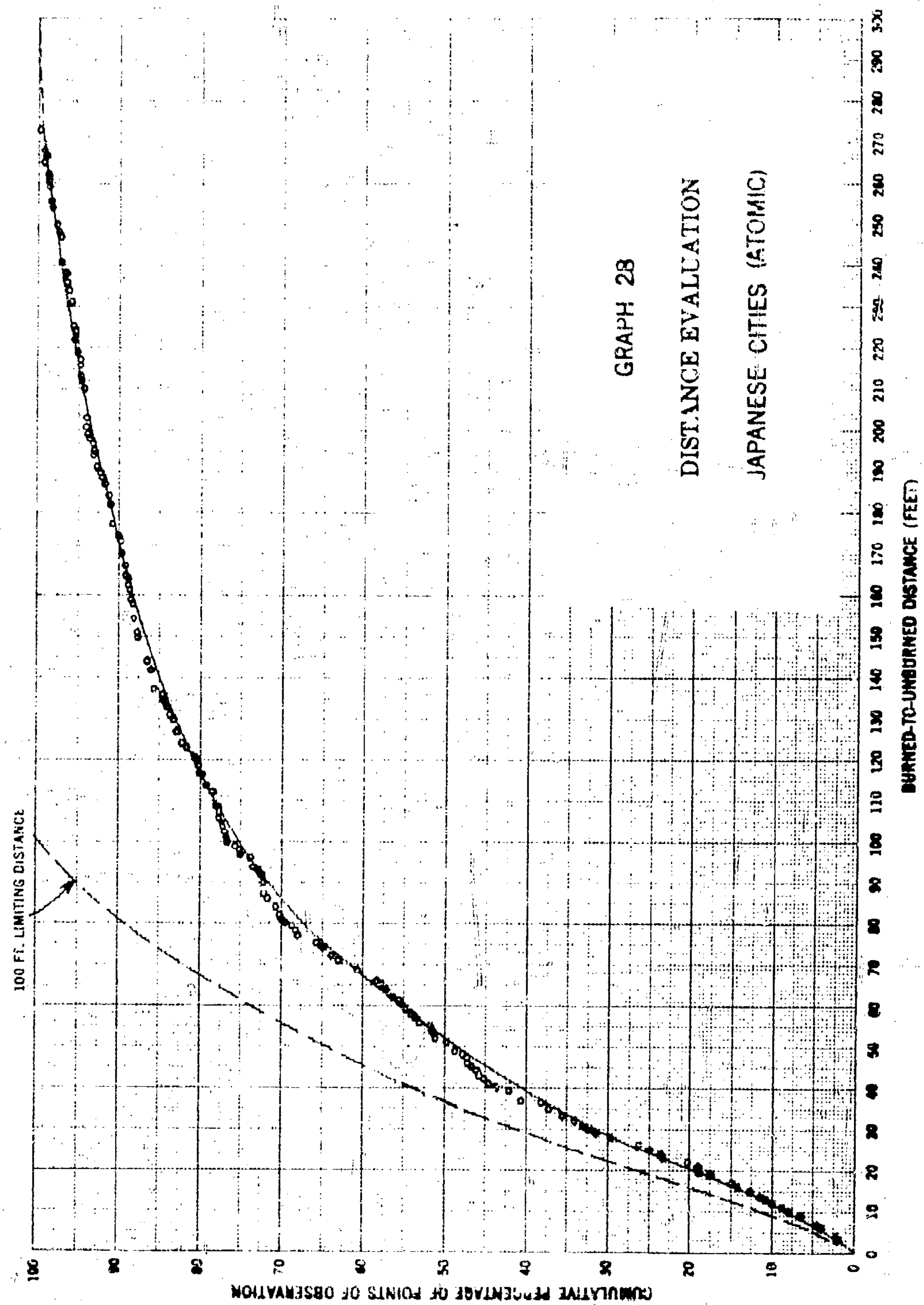

GRAPH 23
DISTANCE EVALUATION
ESSEN
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION

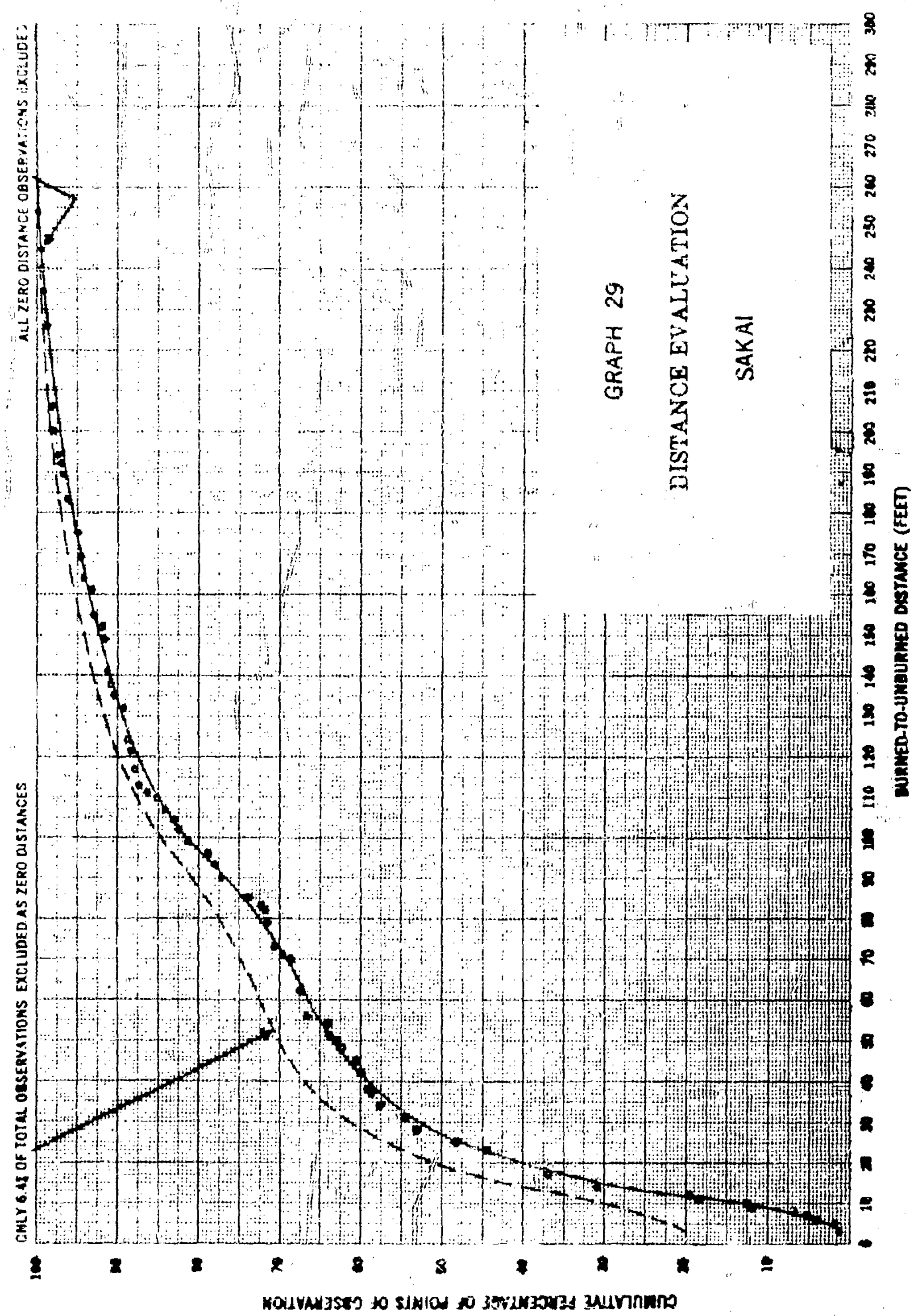

GRAPH 24
DISTANCE EVALUATION
HAMBURG
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION

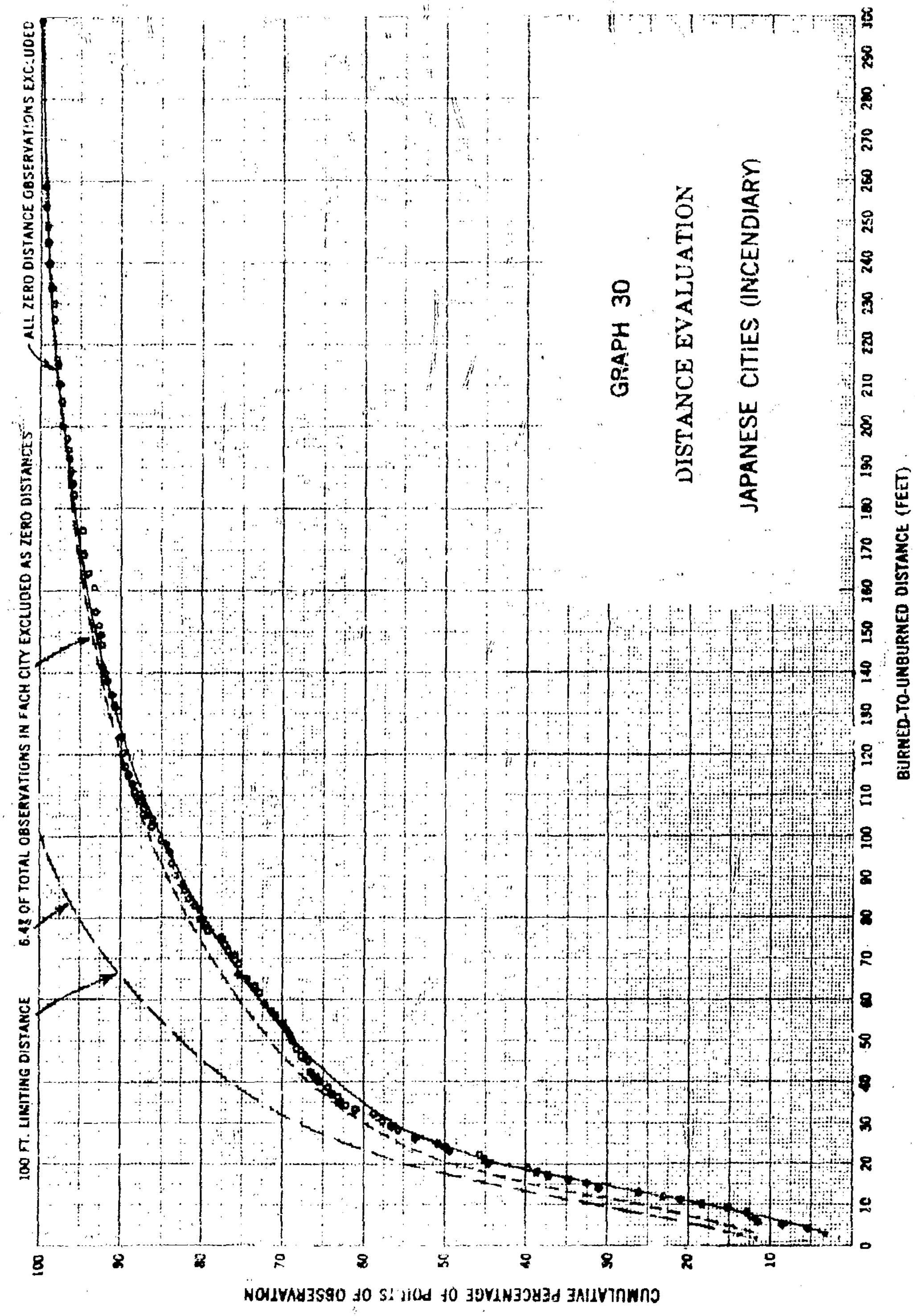

GRAPH 25
DISTANCE EVALUATION
ALL GERMAN CITIES
150 FT. LIMITING DISTANCE
BURNED-TO-UNBURNED DISTANCE (FEET)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
10
20
CUMULATIVE PERCENTAGE


GRAPH 26
DISTANCE EVALUATION
HIROSHIMA
100 FT. LIMITING DISTANCE
CURVE TRANSPOSED FROM GRAPH 3
(NO LIMITING DISTANCE)
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 27
DISTANCE EVALUATION
NAGASAKI
100 FT. LIMITING DISTANCE
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 28
DISTANCE EVALUATION
JAPANESE CITIES (ATOMIC)
100 FT. LIMITING DISTANCE
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION


GRAPH 29
DISTANCE EVALUATION
SAKAI
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION
ONLY 6.4% OF TOTAL OBSERVATIONS EXCLUDED AS ZERO DISTANCES
ALL ZERO DISTANCE OBSERVATIONS EXCLUDED


GRAPH 30
DISTANCE EVALUATION
JAPANESE CITIES (INCENDIARY)
ALL ZERO DISTANCE OBSERVATIONS EXCLUDED
6.4% OF TOTAL OBSERVATIONS IN EACH CITY EXCLUDED AS ZERO DISTANCES
100 FT. LIMITING DISTANCE
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION

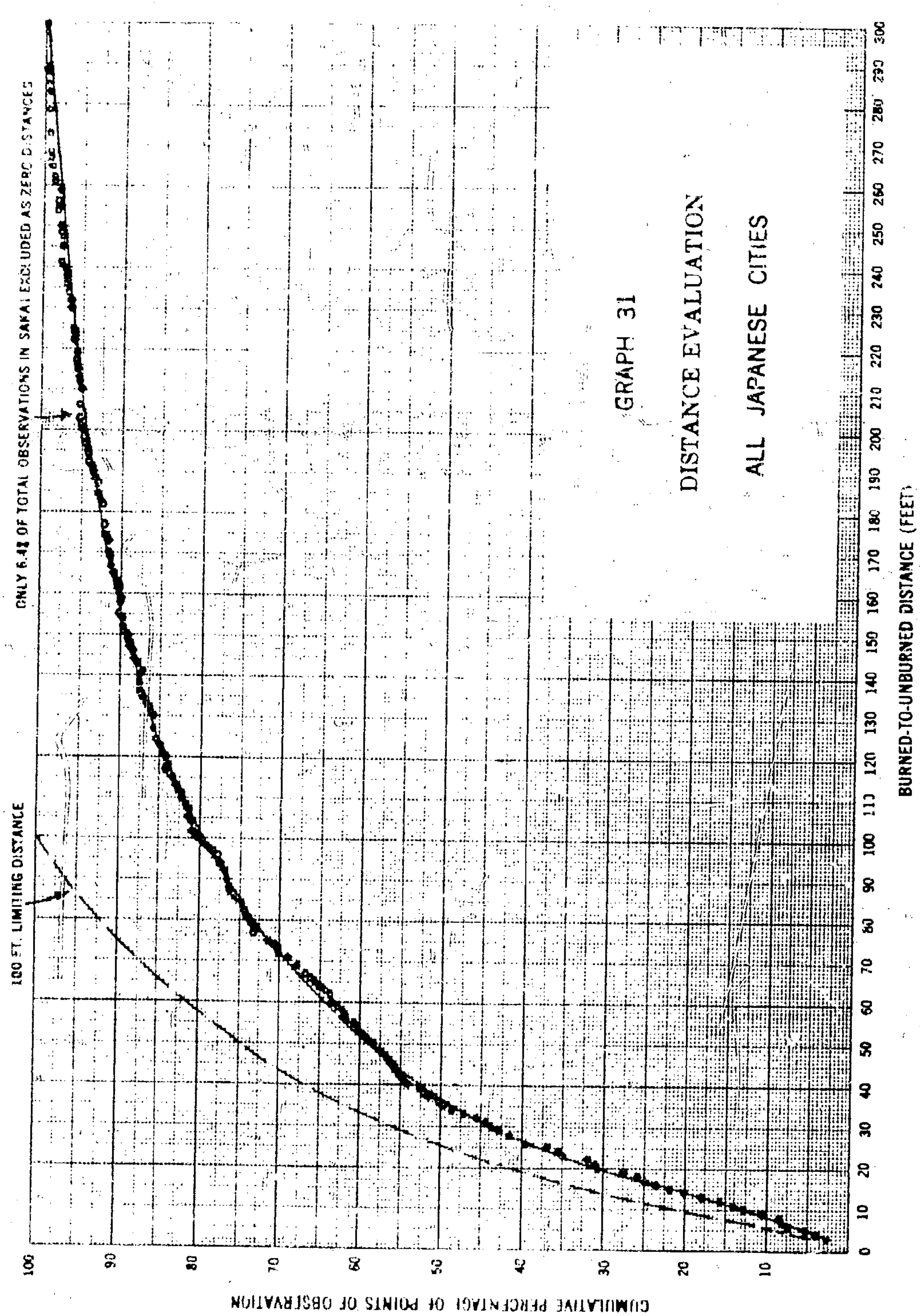

GRAPH 31
DISTANCE EVALUATION
ALL JAPANESE CITIES
ONLY 6.4% OF TOTAL OBSERVATIONS IN SAKAI EXCLUDED AS ZERO DISTANCES
100 FT. LIMITING DISTANCE
BURNED-TO-UNBURNED DISTANCE (FEET)
CUMULATIVE PERCENTAGE OF POINTS OF OBSERVATION

TABLE VIII

DISTANCE EVALUATION

GERMAN CITIES

Burned-to-Unburned Distance (in Feet)	Cumulative Percentage of Points of Observation at which Fire Stopped						
	ELBERFELD	BARMEN	DARMSTADT	KASSEL	ESSEN	HAMBURG	ALL GERMAN CITIES
10	7.0%	4.0%	7.5%	1.5%	7.5%	2.5%	3.5%
20	17.5	14.0	17.5	8.0	19.5	9.0	12.5
30	30.0	25.0	28.0	15.0	31.5	18.0	21.5
40	44.5	38.0	38.0	23.0	46.0	30.0	34.5
50	54.5	47.0	48.0	31.5	58.5	43.5	46.0
60	61.0	53.0	57.0	41.5	67.0	54.0	55.0
70	66.5	58.5	65.0	50.5	73.5	62.5	62.0
80	72.0	63.0	71.5	57.0	78.0	68.5	67.5
90	74.5	67.0	77.5	62.0	81.5	74.0	72.5
100	78.0	70.5	82.0	66.0	84.5	78.5	76.5
110	81.0	74.0	85.5	69.5	87.0	82.0	79.5
120	83.5	76.5	88.0	72.5	89.0	84.5	82.0
130	86.0	79.0	90.0	75.0	90.5	87.0	84.5
140	87.5	81.5	92.0	77.5	92.0	89.0	86.0
150	89.0	83.5	93.0	79.5	93.5	90.5	87.5
300	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Number of Points of Observation:	162	238	170	119	119	497	1305
Graph Number	5	6	7	22	23	24	25

TABLE IX

DISTANCE EVALUATION
JAPANESE CITIES

Burned-to-Unburned Distance (in Feet)	Cumulative Percentage of Points of Observation at which Fire Stopped						
	HIROSHIMA	NAGASAKI	JAPANESE CITIES (Atomic)	SAKAI	KURE	JAPANESE CITIES (Incendiary)	ALL JAPANESE CITIES
10	6.0%	13.0%	8.0%	12.5%	19.0%	18.5%	12.5%
20	15.0	27.0	19.5	40.0	41.5	43.0	30.5
30	25.0	45.5	31.5	53.0	58.0	56.5	43.5
40	34.0	58.0	40.5	59.0	67.0	63.5	52.0
50	42.0	65.5	48.5	63.5	73.5	68.5	58.5
60	49.0	71.0	55.0	66.5	78.5	73.0	64.0
70	56.0	76.0	61.0	69.0	83.0	76.5	68.5
80	62.0	79.5	67.0	72.5	86.5	80.0	73.0
90	67.0	82.0	71.5	76.5	89.5	82.5	76.5
100	71.0	84.0	75.0	81.5	91.5	85.0	79.5
110	74.5	86.0	78.0	85.0	93.5	87.0	82.0
120	77.5	87.0	81.0	87.5	95.0	89.0	84.5
130	80.5	88.0	83.0	89.5	96.5	90.5	86.0
140	83.0	82.5	85.0	91.0	97.5	92.0	88.0
150	85.0	89.5	87.0	92.5	98.0	93.0	89.5
300	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Number of Points of Observation:	475	201	676	243	293	536	1212
Graph Number	26	27	28	29	8	30	31

than in Sakai (see Graphs 8 and 29, and Table IX). It will also be noted that the percentage of zero-distance measurements (23.8 per cent) for Sakai is several times the percentage for Kure or any of the other Japanese cities (see Table X). Much of the photography covering Sakai was of small scale and hazy quality: better quality photography probably would have shown that there was actually some distance between buildings in many of the instances where open space was not discernible. Also, with the over-hanging roof eaves prevalent on Japanese structures, it is possible to have some open space between buildings where on aerial photography, especially hazy photography, there would appear to be a continuous roof. If it were assumed that in Sakai the ratio of the true number of zero distances to the total number of points of observation was the same as established for Kure (6.4 per cent), the broken line curve on Graph 29 is obtained and there is much better correlation between the curves for the two cities. The broken line curves on Graph 30 represent the consolidated data for Kure and Sakai based on this revision of the Sakai data.

TABLE X

ZERO-DISTANCE OBSERVATIONS

City	Total Number of Observations	Observations at Zero Distance	
		Number	Per Cent of Total
German			
Elberfeld	228	66	28.9
Barmen	264	26	9.8
Darmstadt	204	34	16.7
Kassel	168	49	29.2
Essen	188	69	36.7
Hamburg	731	234	32.0
Total	1783	478	26.8
Japanese			
Hiroshima	495	20	4.0
Nagasaki	213	12	5.6
Sakai	319	76	23.8
Kure	313	20	6.4
Total	1340	128	9.6

The curves for Hiroshima and Nagasaki show that greater distances were required to stop spread of fire in Hiroshima than in Nagasaki. Since construction within the two cities was of the same type and presumably the contents loading was similar, and since wind and other meteorological conditions are known to have been about the same, the variation was probably

caused by differences in bomb placement in relation to built-up areas and topographic features, and in firefighting activity.1/ In Hiroshima, the bomb ground zero location was surrounded by heavily built-up area for at least 5000 feet in all directions. In contrast, the Nagasaki bomb detonated over a rather narrow valley and the heavily built-up area extended less than 3000 feet from ground zero in all except the southerly direction. Consequently, a large proportion of the final fire perimeter in Nagasaki probably resulted from the merging of initial fires started by the bomb rather than from the outward spread of a fire front. Along the southern segment of the fire perimeter in Nagasaki, there was firefighting activity by the public fire department, whereas in Hiroshima a large part of the public fire department apparatus and personnel were immediate casualties of the atomic bomb. In addition, a higher proportion of the general populace in Hiroshima became casualties and this further restricted the amount of firefighting.

Comparison of the consolidated curve for Kure-Sakai (Graph 30) with that for Hiroshima-Nagasaki (Graph 28) shows that, for a given burned-to-unburned distance, the percentage of points of observations was larger in the incendiary-attacked cities than in the atomic-attacked cities. Stated another way, shorter distances were generally more successful in stopping spread of fire in the incendiary-attacked cities. The most important factors which could account for this difference are as follows:

(1) The cities expected and were prepared to some extent for incendiary bomb attacks, but not for atomic attacks.

(2) Ignitions were practically simultaneous in the atomic attacks, whereas they were spread out over a period of time in the incendiary attacks.

(3) In the atomic attacks, severe blast damage occurred simultaneously with the ignitions and combustible debris was strewn across streets and between buildings. This had the effect of reducing or eliminating the clear space and providing a direct means of fire spread.

(4) The atomic attacks caused severe damage to firefighting apparatus and high casualties among fire department personnel and the urban populace as whole. As a consequence, firefighting was reduced to a minimum and efforts were concentrated on rescue work and self preservation.

Comparison of the consolidated curve for the six German cities (Graph 25) with that for the atomic-attacked Japanese cities (Graph 28) shows that they very nearly coincide. On the other hand, the consolidated curve for Kure and Sakai (Graph 30), when compared with that for the six German cities (Graph 25), verifies the results of the preliminary analysis in Test II, to the effect that fire spread was stopped by much shorter distances in the incendiary-attacked Japanese cities than in the incendiary-attacked German cities.

1/ A Report on Physical Damage in Japan, U. S. Strategic Bombing Survey, Physical Damage Division, Report No. 96, June 1947, pp 197-199.

Comparison of the cumulative points-of-observation curve for Hiroshima (Graph 26) with the U.S.S.B.S. curve for Hiroshima (Graph 3) shows considerable divergence. It is important to note that Graph 26 represents the relationship of fire stoppage to distance whereas Graph 3 represents the relationship of fire spread to distance. Therefore, only the distances corresponding to the 50 per cent points on the two curves can be compared directly; as an example, the distance corresponding to 30 per cent on Graph 26 must be compared with the distance corresponding to 70 per cent (100 minus 30) on Graph 3. The curve of Graph 3 has been transposed onto Graph 26 to illustrate the true comparison. The two curves cross at 47.5-foot distance and the divergence is 10 feet or less at shorter distances. There is wide divergence at greater distances but this is easily explained by the fact that 46.5 per cent of the data for Graph 3 was for observed distances in excess of 100 feet, whereas only 29 per cent of the points-of-observation data for Graph 26 was for distances exceeding 100 feet. In collecting the data for Graph 26, points of observation for distances exceeding 300 feet were excluded; on the other hand, no distance limitation was set when the data for Graph 3 were collected. If the 29 per cent figure were used instead of 46.5 per cent in developing Graph 3, the revised curve would coincide with Graph 26 curve at the 100-foot distance and the principal discrepancies would be at distances less than 100 feet. Actually, there is fairly good agreement between the two curves, considering the fact that Graph 3 was developed by the cumulative percentage of length-of-perimeter method, whereas Graph 26 was developed by the cumulative percentage of points-of-observation method. Graph 26 is considered more reliable because much more detailed measurements were made in collecting the data; besides, use of observed distances with no upper limit unduly influences the shape of the curve - it is more reasonable to assume that there is a limiting distance across which fire cannot be expected to spread.

All of the consolidated curves for cumulative points of observation versus corresponding distances from burned-to-unburned buildings are based on measurements of distances across which fire failed to spread. The question arises as to whether these curves can be used as probability curves for estimating the probability that a given distance separating a burning building and an exposed building will prevent spread of fire. Technically, in order to establish probability curves, points of observation are necessary for all instances where fire spread from one building to another as well as for all instances where fire did not spread. It was impossible to make analyses of the burned areas which would provide the necessary observations of where fire did spread because it was not known which buildings burned due to direct hits nor the sequence or direction of fire spread from building to building. Since the consolidated curves reflect the average effect of numerous variables in the types of cities studied, it would seem reasonable and practicable to select and use one of the curves as a probability curve where the over-all conditions in the urban area under analysis can be expected to be similar to the average conditions which produced the data.

There may be a basic objection to making practical application of the consolidated cumulative points-of-observation curves as probability curves because the distance data used in developing them consisted entirely of measurements where fire did not spread from a burning building to an exposed building. Obviously, wherever fire failed to spread across a certain distance, it also might not have spread across a lesser distance. The

significance of this deficiency probably is minimized: (1) if the total data sample is large and it contains numerous observations of various distances at the final fire perimeter; and (2) if there was, in fact, an outwardly advancing fire front at the fringe of the burning area, in which case it can be assumed that the potential of fire spreading from building to building was tested by a wide variety of distances before stopping at the final fire perimeter. It is believed that these two suppositions are fairly well satisfied by the quantity and distribution of the data, and by the fire spread characteristics of the conflagrations studied.

In measuring distances where fire did not spread, it was necessary to select a limiting distance across which fire could not be expected to spread. The limiting distance used in collecting the data and in developing the consolidated curves was 300 feet. However, nearly 90 per cent of the total points of observation in the German cities and in the Japanese cities were for distances of 150 feet or less. Selection of the limiting distance has a very important effect on the form of the cumulative points-of-observation curves. This is illustrated by the broken-line curves shown on Graph 25 for a limiting distance of 150 feet in the German cities, and on Graphs 26, 27, 28, 30 and 31 for a limiting distance of 100 feet in the Japanese cities. A greater limiting distance for German cities is justified because of the heavier fuel or fire load in them. If desired, any one of the curves can be adjusted for any limiting distance less than 300 feet by recomputing the percentages in the corresponding table on the basis of the decreased number of observations, and then replotting the curve. Curves with a limiting distance of less than 300 feet may be more acceptable for use as probability curves because they would produce more conservative estimates of fire spread, i.e., they would be less likely to overestimate the fire vulnerability of an urban area.

PART V

CONCLUSIONS

The consolidated curves for either the German cities or the Japanese cities provide a practical basis for estimating the vulnerability of urban areas to fire spread under conditions of mass fire. They may be applied directly if the urban area under analysis is judged to have similar average physical and structural characteristics. The German and Japanese types of city probably represent opposite extremes with respect to building construction, height, and contents loading. Therefore, interpolation of the curves should be feasible for analysis of other urban areas by taking into account the significant differences in structural characteristics and combustible contents loading.

Use of consolidated curves with a limiting distance of less than 300 feet will produce more conservative estimates of fire spread, i.e., the fire vulnerability of an urban area is less likely to be overestimated. A limiting distance of 150 feet is favored for German cities, and 100 feet for Japanese cities.

Greater distances were required to stop fire spread at the final perimeter of the mass fire area in the atomic-attacked cities of Hiroshima and Nagasaki than in the incendiary-attacked cities of Kure and Sakai.

Construction and size of building and type and quantity of contents, which determine the fuel or fire load of an urban a a, have a very important effect on fire spread. This accounts for the finding that, in areas of the same building density or volume, greater distances were required to stop spread of fire in German cities than in Japanese cities.

Building density is an important factor in the fire spread characteristics of an urban area, but building volume reflects building height as well as density and, therefore, provides a better representation of fuel on fire load. Neither building density nor building volume can be considered independently of other factors, however, in estimating the vulnerability of an urban area to fire spread.

Fire walls and party walls played a part, although a relatively minor one as compared to building separation, in halting spread of fire at the final fire perimeter. Within the fire perimeter these walls were generally ineffective because they were outflanked by the initial fires or by spreading fires.

PART VI

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DEPARTMENT OF THE AIR FORCE
WASHINGTON, DC

1 November 2005

MEMORANDUM FOR DTIC-RS
Attn: Kelly D. Akers
8725 John J. Kingman Rd., STE 0944
Ft. Belvoir, VA 22060-6218

FROM: HAF ICIOD (FOIA)
1000 Air Force Pentagon
Washington, DC 20330-1000

SUBJECT: Freedom of Information Act Request – DTIC # 2002-67 (Baker)

1. Reference the attached DTIC referral of the report AD0094651, "Fire Spread in Urban Areas," which was forwarded to this office for review and release determination.

2. The document was declassified by AF/XOI effective 28 Oct 2002 and released to the requester on 1 Nov 2005. As a result of this public release there are no restrictions on future releases in response to requests. A copy of the cover page with the appropriate markings is also enclosed.

PENNY JENKINS
Freedom of Information Act Manager

2 Attch
As stated

DEFENSE INFORMATION SYSTEMS AGENCY
DEFENSE TECHNICAL INFORMATION CENTER
8725 JOHN J KINGMAN RD STE 0944
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IN REPLY REFER TO DTIC-RS (FOIA 2002-67)

SUBJECT: Freedom of Information Act (FOIA) Program

TO: Commander
CL-P, 11 CS/SCSR (FOIA)
1000 Air Force Pentagon
Washington, DC 20330-1000

1. Reference FOIA request from Mr. Nicholas Baker, dated June 13, 2002 (enclosed).

2. Release of document AD0094651, entitled *Fire Spread in Urban Areas,* may only be performed by the appropriate Air Force controlling activity. Therefore, we are forwarding this request to you for processing and direct response back to Mr. Baker. We have notified Mr. Baker of this action. Our records indicate the document is classified and was produced by the Directorate of Intelligence, USAF, Washington, DC, and assigned report number TM PVTM 16.

3. Should your review of this document result in a determination to declassify and/or delimit it (make available to the public) or a determination that the distribution statement on the document should be changed, please advise this office in writing we we may mark our records accordingly.

4. If you need a copy of the document to review, contact our Reference and Retrieval Services office at (703) 767-8274 for instructions on obtaining documents from the Defense Technical Information Center (DTIC). The category of this request was "news media." Mr. Baker incurred no assessable fees for services from DTIC. If you have any questions, please call me at (703) 767-9194 or DSN 427-9194.

FOR THE ADMINISTRATOR:

Kelly D. Akers

KELLY D. AKERS
FOIA Program Manager

1 Encl a/s

Atch 1